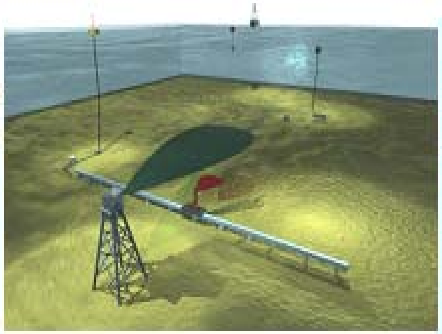
Broadband, Multi-Aspect Scattering from Proud and Buried UXO



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14. ABSTRACT

Sonars which form high resolution images operate at high frequencies where the acoustic wavelengths are short compared to the target dimensions and the waves are scattered predominately from the geometric target boundary. In the structural acoustic regime where acoustic wavelengths are comparable to the target dimensions, sound penetrates the target and the scattered echoes are related to the vibrational dynamics of the object. The time-frequency features in the echoes can then be used to ?fingerprint? the target in addition to examining an image. We have been carrying out studies to evaluate the potential for the detection and identification of unexploded ordnance (UXO) in coastal and inland waters by exploiting their structural acoustic response. We will present and discuss underwater broadband multi-aspect scattering measurements and numerical simulations made on a number of UXO objects and several false targets in the proud and buried condition. The measurements were, for the most part, conducted in the NRL sediment laboratory pool facility. The simulation studies were carried out using two structural acoustic codes ? one time based and the other frequency based ? for treating target, sediment, and acoustic propagation. The UXO scattering data bases include both mono-static and bi-static source/receiver configurations, with both large look-down and near-grazing angle geometries, with the special case of forward scattering included in the latter. These broadband data bases, which can support both standard imaging and structural acoustic feature identification, are being used to train and test relevance vector machine (RVM) and imaging algorithms for identifying the UXO targets and to evaluate how the sediment and associated burial effects impact the identification process.

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BROADBAND, MULTI-ASPECT SCATTERING FROM PROUD AND BURIED UXO

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T. Yoder and L. Kraus (Global Defense Technology & Systems, Inc. [GTEC])

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Outline

Background

- Three UXO Search Scenarios
- Imaging and Structural Acoustic ID

Long Range Mono-static Scenario

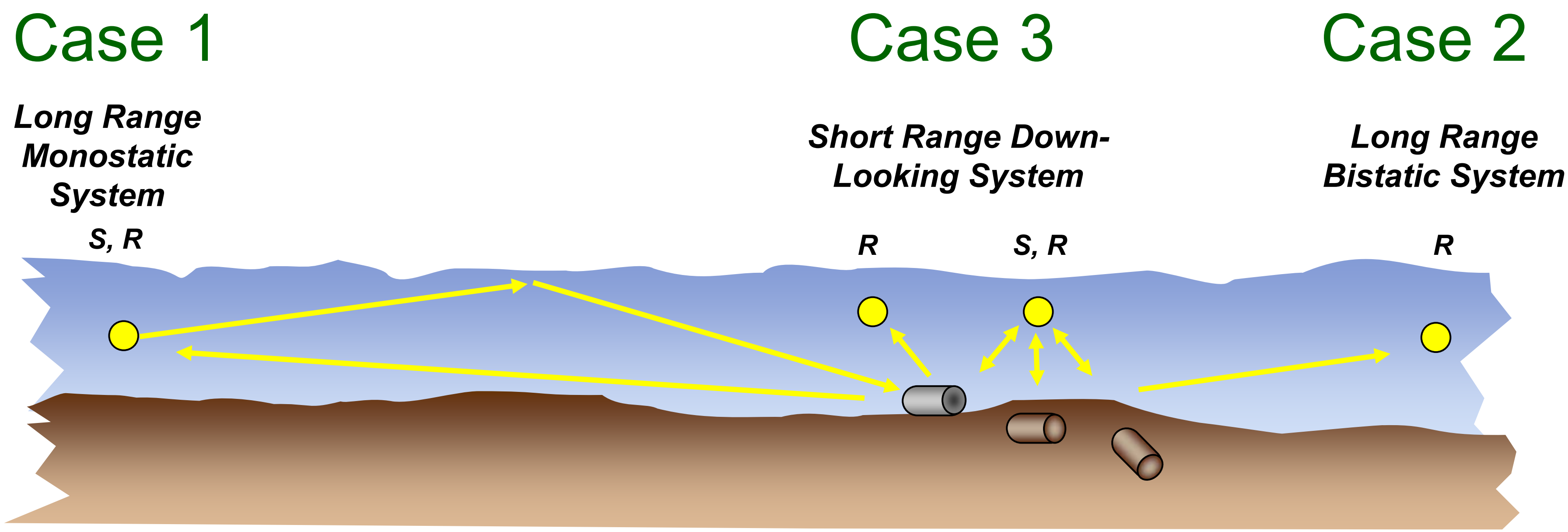
Bi-static Forward Scattering Scenario

Short-range Down-looking Scenario

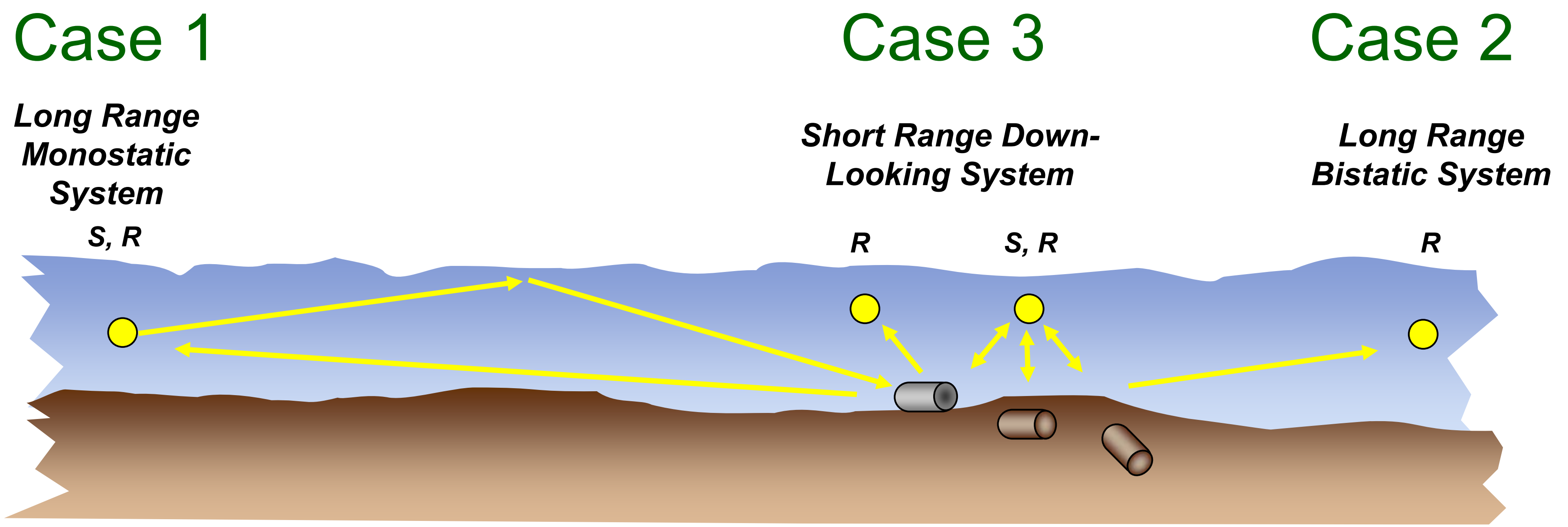
- Numerical Simulations for Buried Targets
- Sediment Facility Measurements

Future Plans

The Three UXO SONAR Configurations



The Three UXO SONAR Configurations



- High Coverage Rates
- Low Sediment Penetration

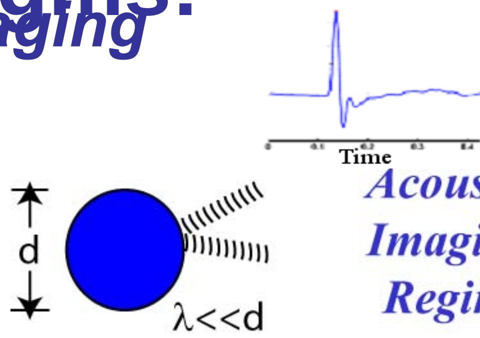
- Good Sediment Penetration
- Lower Coverage Rates

Background

The Two Target *ID* Paradigms:

Imaging

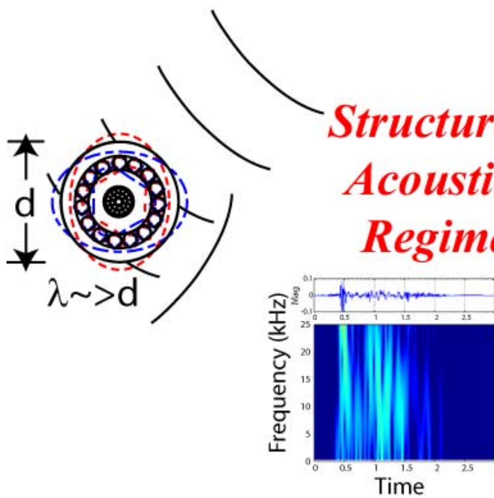
Time-delay in specular echoes processed to form image of target's shape



Acoustic Imaging Regime

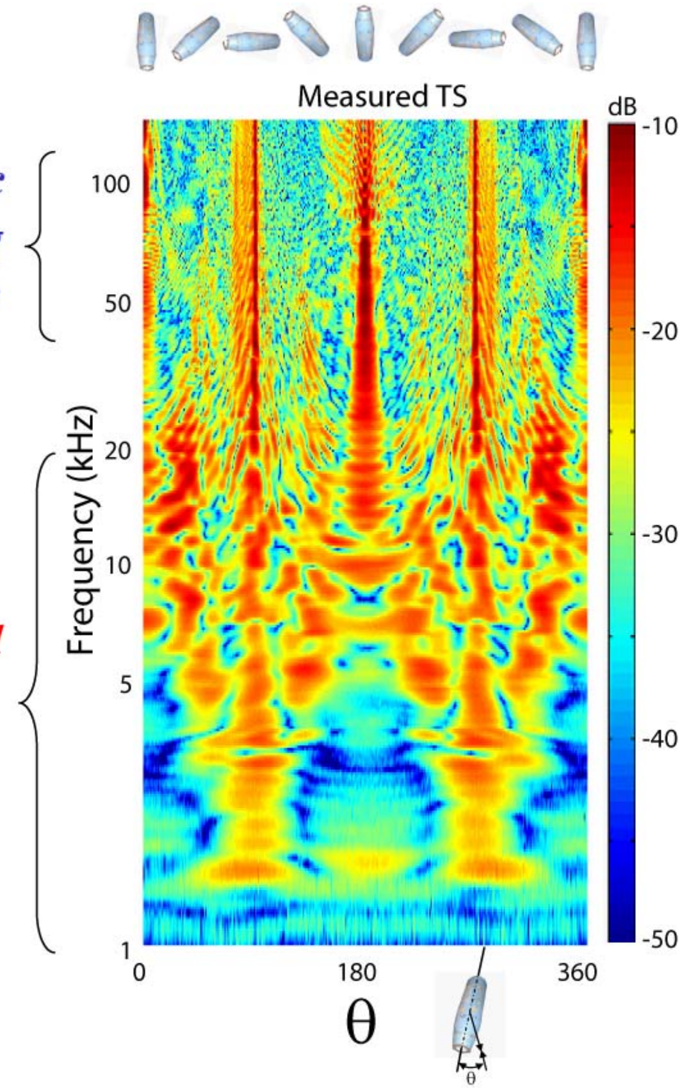
Structural Acoustic ID

Echo related to vibrations of casing & internals. Time-frequency features used to "fingerprint" target.

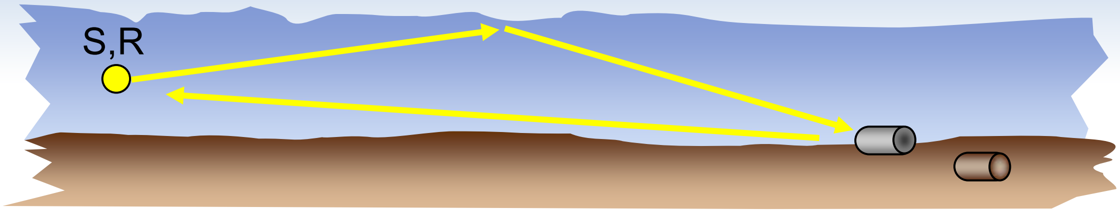


Structural Acoustic Regime

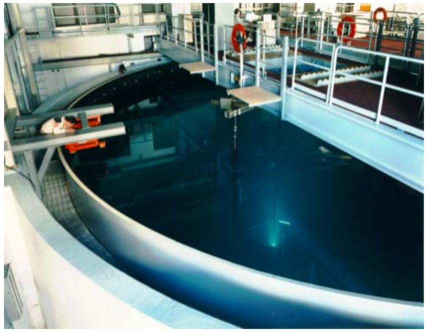
UXO Echo Frequency/Angle Spectrum

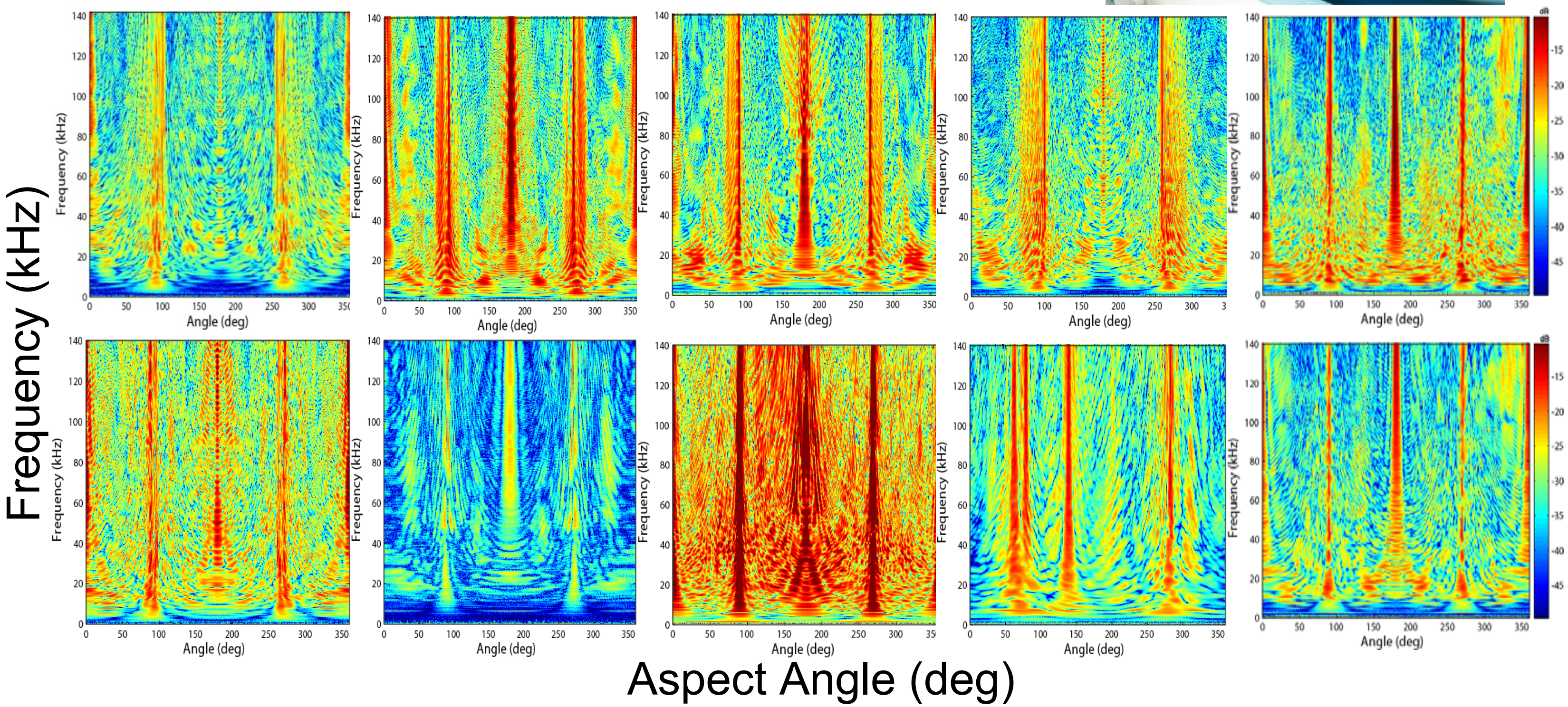


Long range mono-static system (Case 1)



Broadband Echo Data on Six UXO and Four False Targets





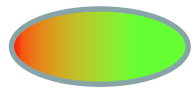
Structural Acoustic Feature-Based ID

Features Obtained from Measured UXO Echo Frequency/Angle Spectrum

Kernal Classifiers / RVM (KMP)

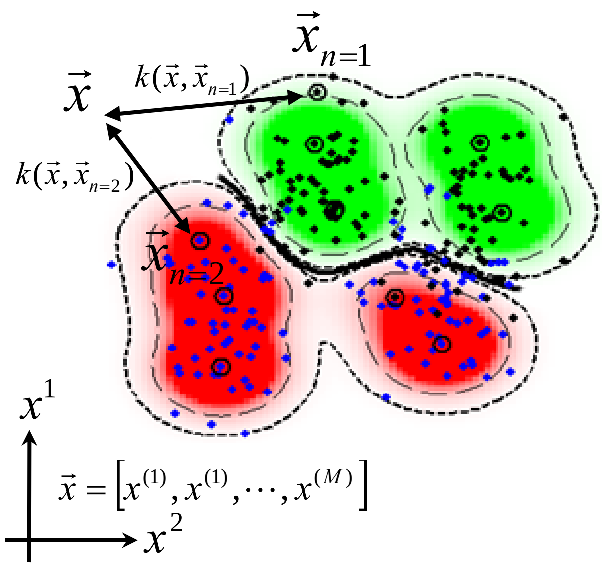
Kernal Classifiers

$$y(\vec{x}) = \sum_{n=1}^{N} \alpha_n k(\vec{x},\vec{x}_n) - \alpha_0$$

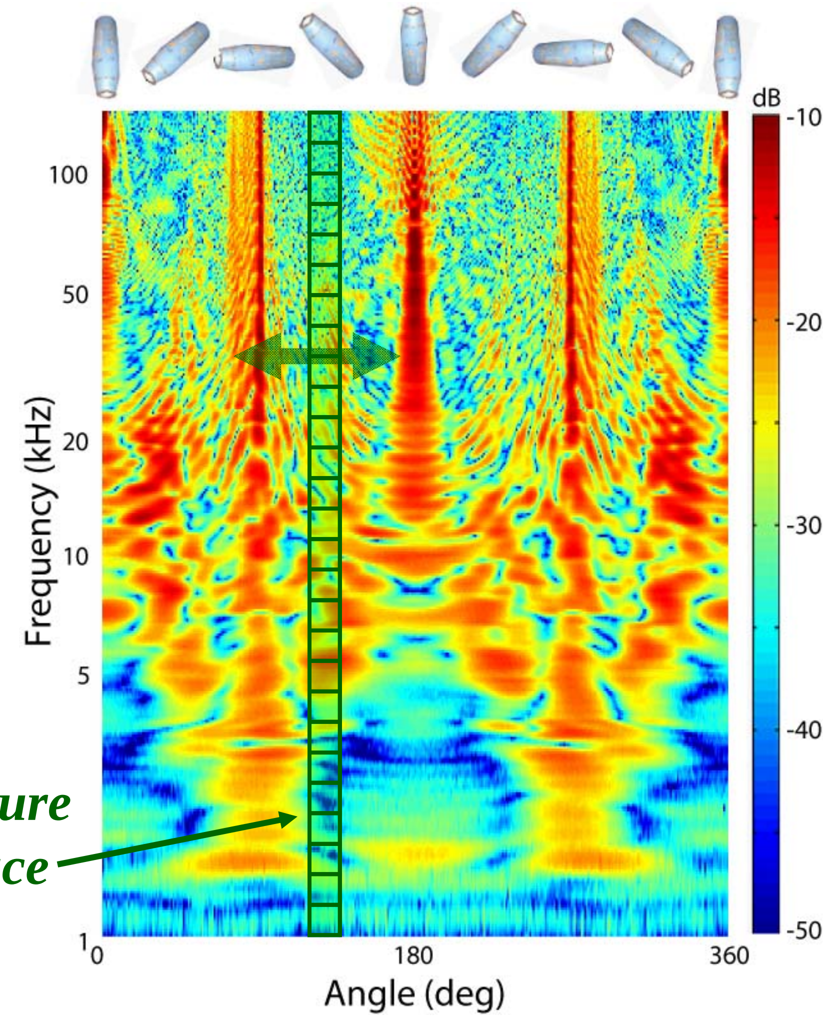


RVM

Minimize the error
Minimize the # of relevant vectors
(force most $\alpha \rightarrow 0$)



Semi-Log Frequency Plot



Feature Space

Target ID Using Structural Acoustic Features

ID Algorithm Trained and Tested with Laboratory Data

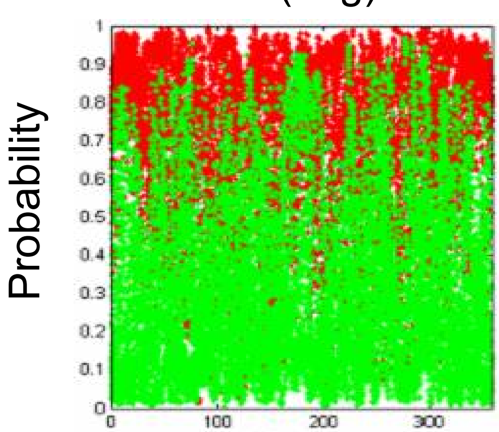
Grouping # 2	Cinder Block/Rock/Pipes	UXO

Clutter

Ordnance

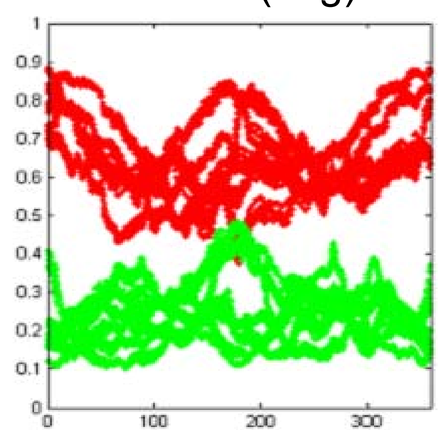
Probability of Correct Identification

± 0 (deg)



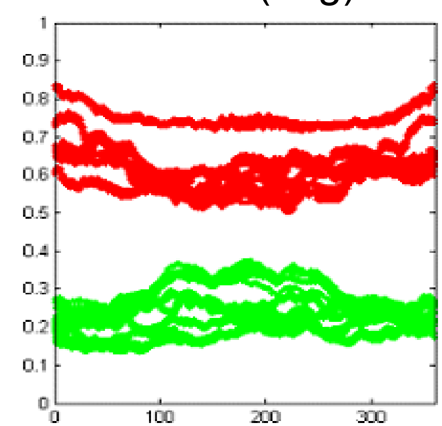
θ (deg)

± 30 (deg)



θ (deg)

± 75 (deg)



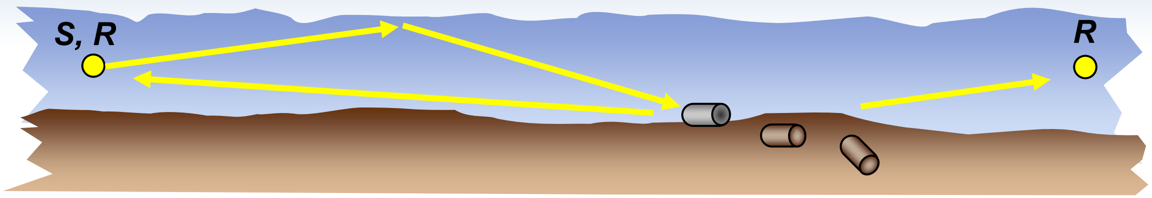
θ (deg)

Target ID Using Structural Acoustic Features

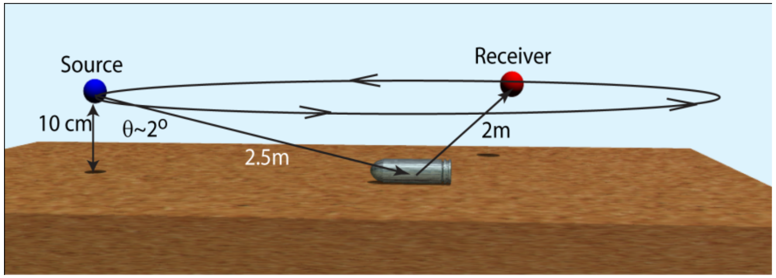
- RVM trained with noise corrupted lab data
- Thirty four cases tested in the lab: all showed good separation

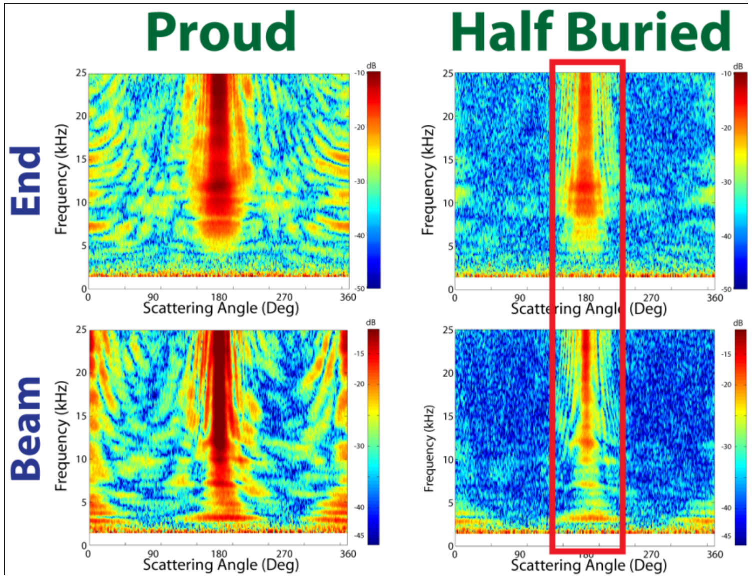
Test #	Target Grouping	False Targets
1	Explosive Simulators	All Others
2	Ordnance Related	Cinder Block/Rock/Pipes
3	Bodies of Revolution	Cinder Block/Rock
4	Mortars	All Others
5	Pseudo-cylinder/Explosive	Cinder Block/Rock/Pipes
6	Mortars	Cinder Block/Rock/Pipes
7	Small Cartridge	Cinder Block/Rock/Pipes
8-14	One Ordnance at a time	Cinder Block/Rock/Pipes
15	Small Cartridge	Cinder Block/Rock
16-26	One Target at a Time	All Others
27	Ordnance Related	Cinder Block/Rock/Noise
28-33	One Ordnance at a Time	All Other Ordnance
34	Wet Mortar	All Other Ordnance

Long Range Bi-static System (Case 2)



Bi-static echo for source at end & beam in the sediment facility

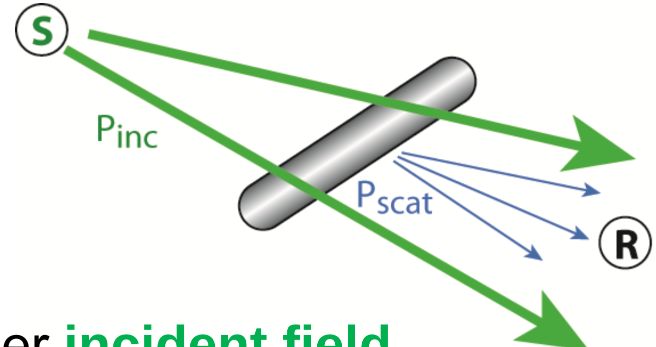




Forward Scatter

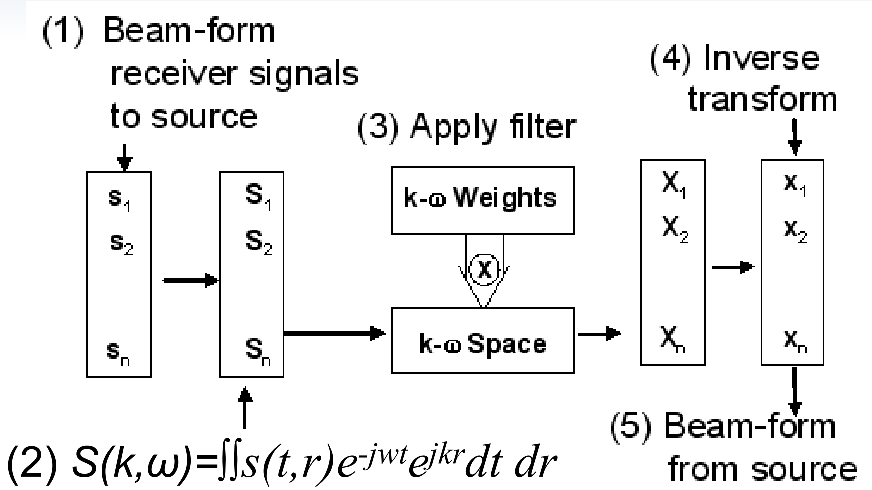
- Highest TS at all θ_{inc}
- Robust upon burial

But . . .



Echo masked in the much stronger **incident field**.

Extraction of Forward Scatter Echo via Wave-number Filtering



$$P_{INC} \rightarrow P_S\, r_{sr}^{\,-1} \exp ik_S\,(r_{sr} + \Delta r_{sr}(n))$$

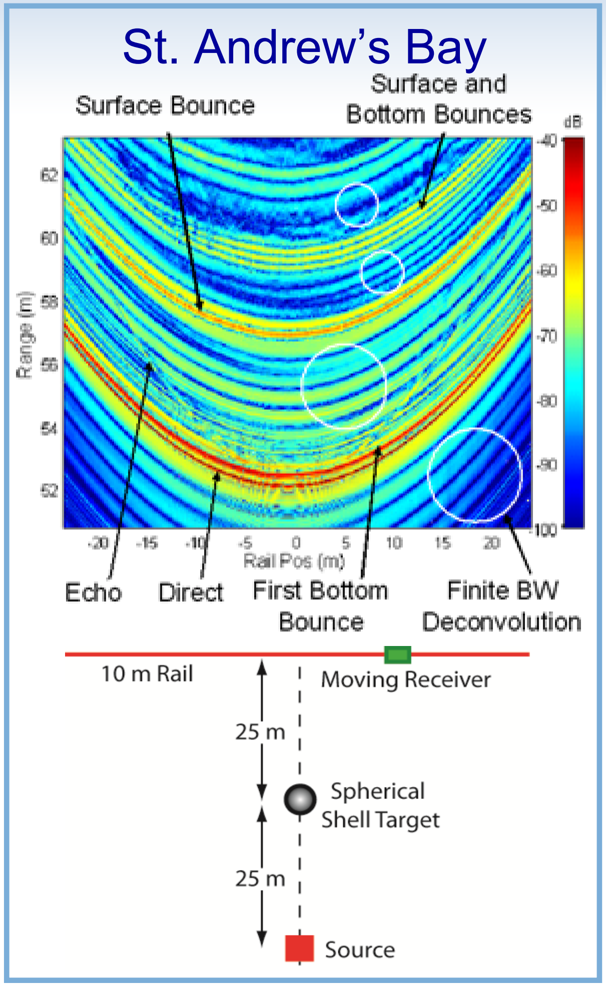
(1) $\rightarrow\ P_S \exp ik_S\, \Delta r_{sr}(n))$

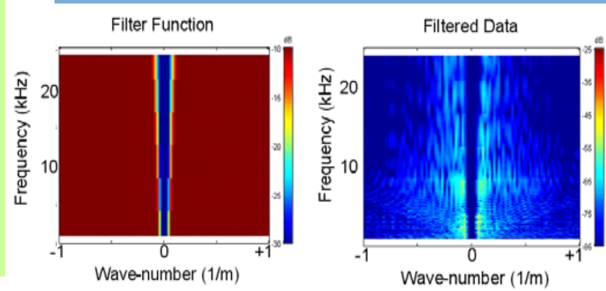
(2) $\rightarrow\ \int dr \exp(-ikr) \exp ik_S\, \Delta r_{sr}(n)) \sim \delta(k) + \xi(k)$

(3) Apply filter $\mathcal{F}(k) = \begin{cases} 0 \text{ for } k \approx 0 \pm \Delta k \\ 1 \text{ elsewhere} \end{cases}$

Filter bandwidth $\Delta k = k\, \Delta r/r\text{'s} = \omega/C_0 \cdot \Delta r/r$

$\Delta r\text{'s} \sim 0.05\text{m} \rightarrow \Delta k(20 \text{ kHz}) \sim 0.1\text{m}^{-1}$

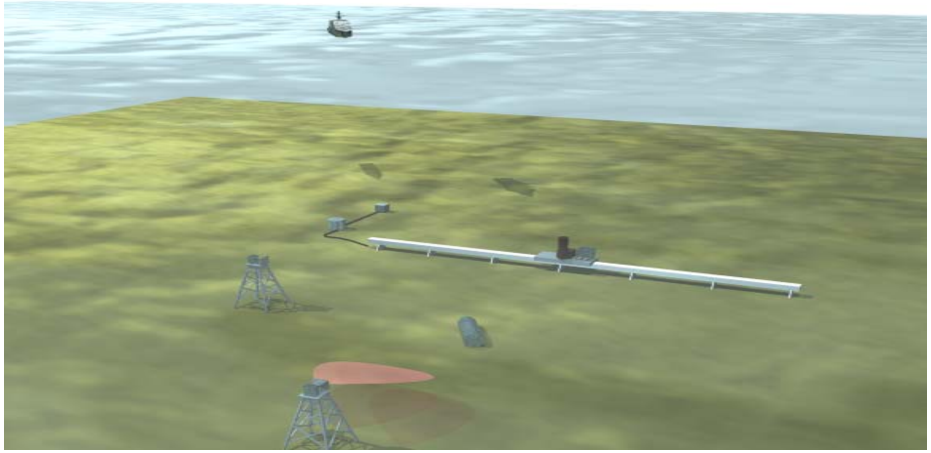


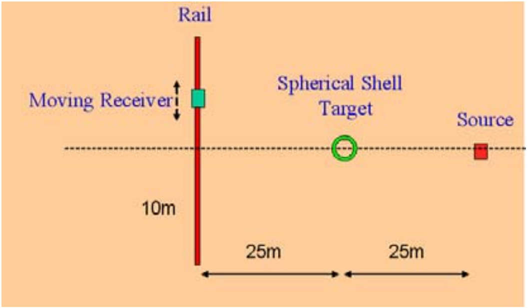


Prosecuting Forward Scattering in a Marine Environment (Case 2)

- Gulf of Mexico with ~ 40 ft water depth
- Forward scatter of proud spherical shell (12” radius)

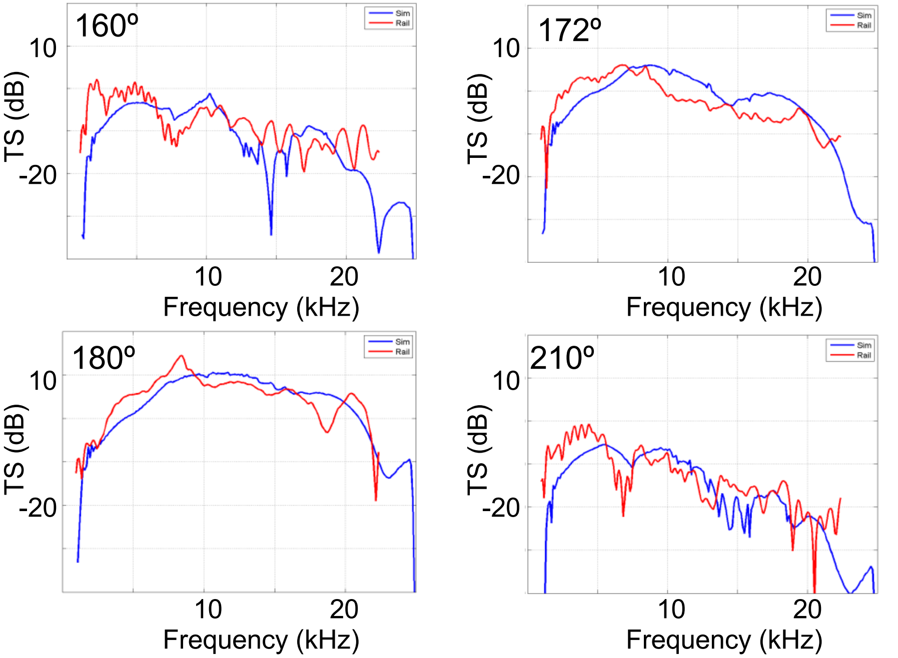
St. Andrew’s Bay





Extraction of Forward Echo via Wavenumber Filtering

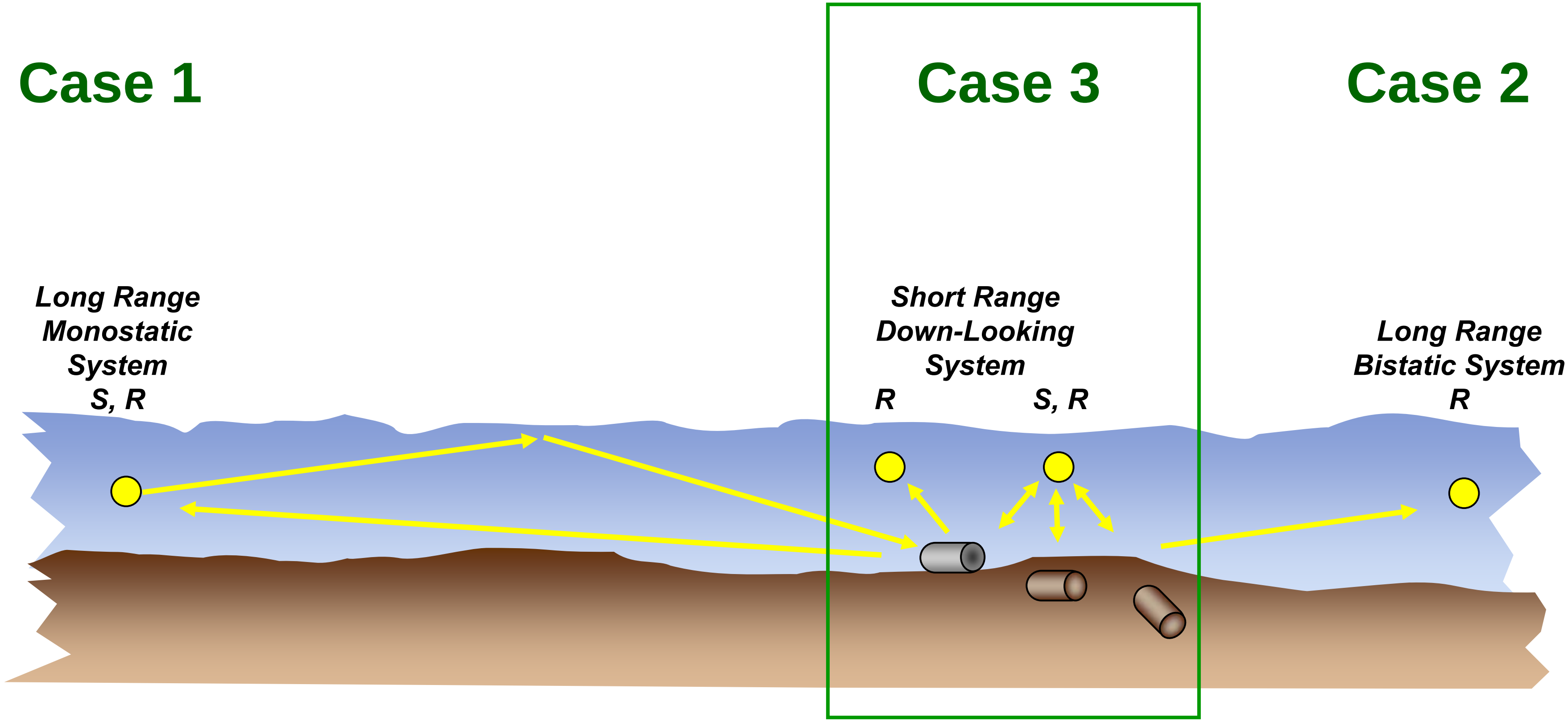
Gulf Rail Measurements vs Simulation using Free-Field



- Extraction technique also applicable to backscattered echo/clutter

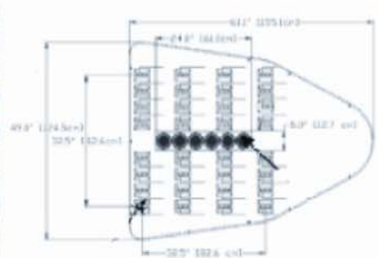
Case 3

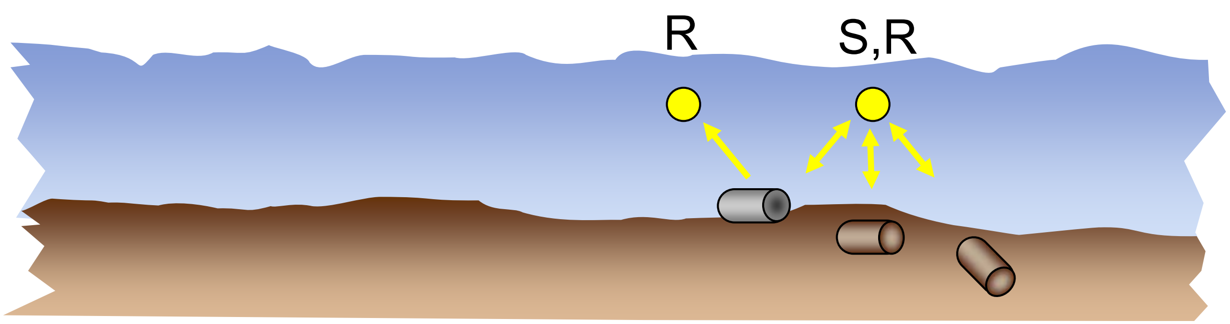
The Look-Down SONAR Configuration



Short Range Down-Looking System

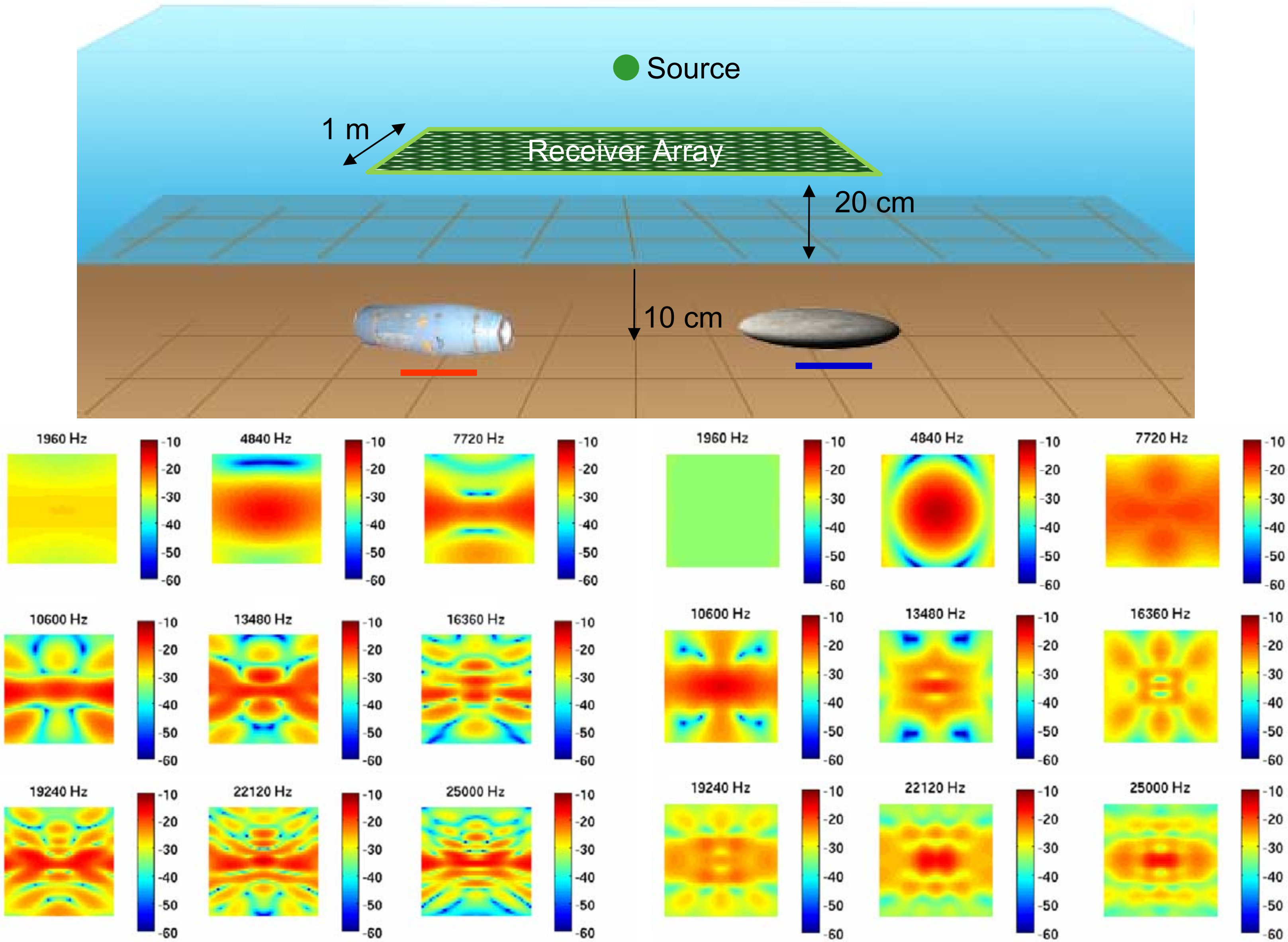
A down-looking, limited angle bi-static structural acoustic sonar could be implemented with the Bottom Object Sonar System (BOSS) developed by S. Schock

Towed BOSS Configuration with Bottom Sources/Receivers	**AUV-based BOSS with Extended Receiver Arrays**
 	



STARS 3D Numerical Simulation

Looking down at buried 5-inch rocket & large rock



Extension of 2D ID Algorithm

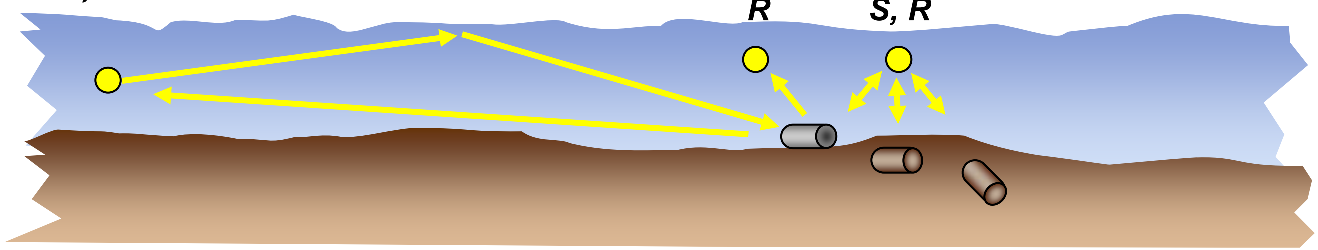
Look-Down Case

Case 1

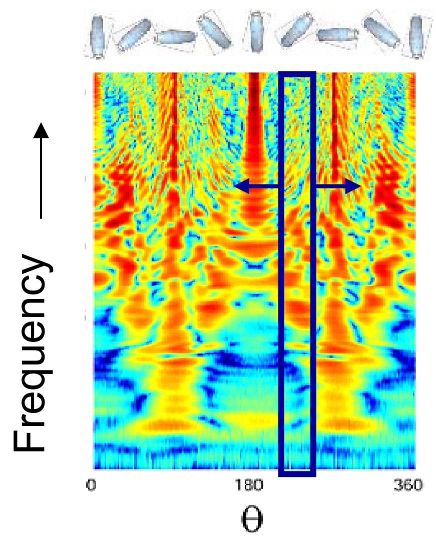
Long Range Monostatic System
S, R

Case 3

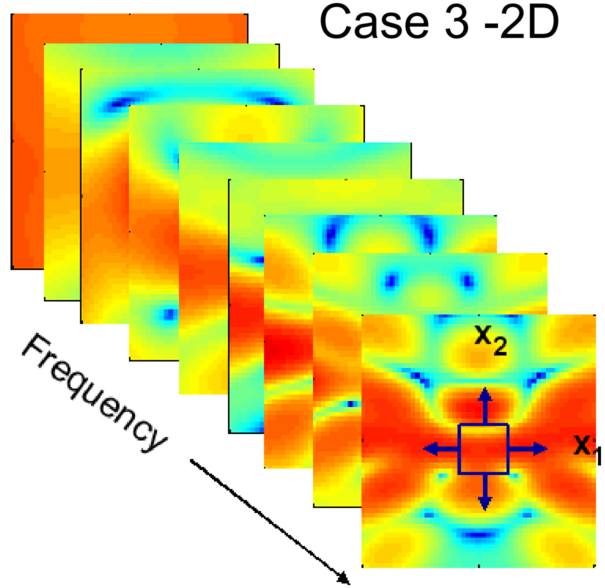
Short Range Down-Looking System



Our Present RVM
Case 1 – 1D



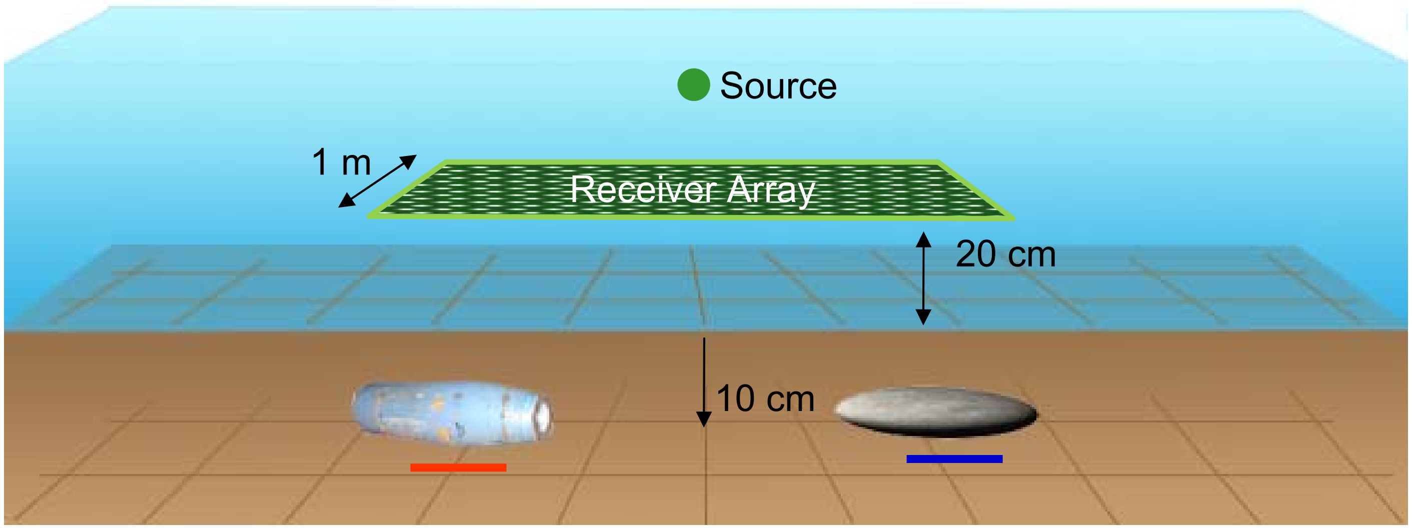
Case 3 -2D



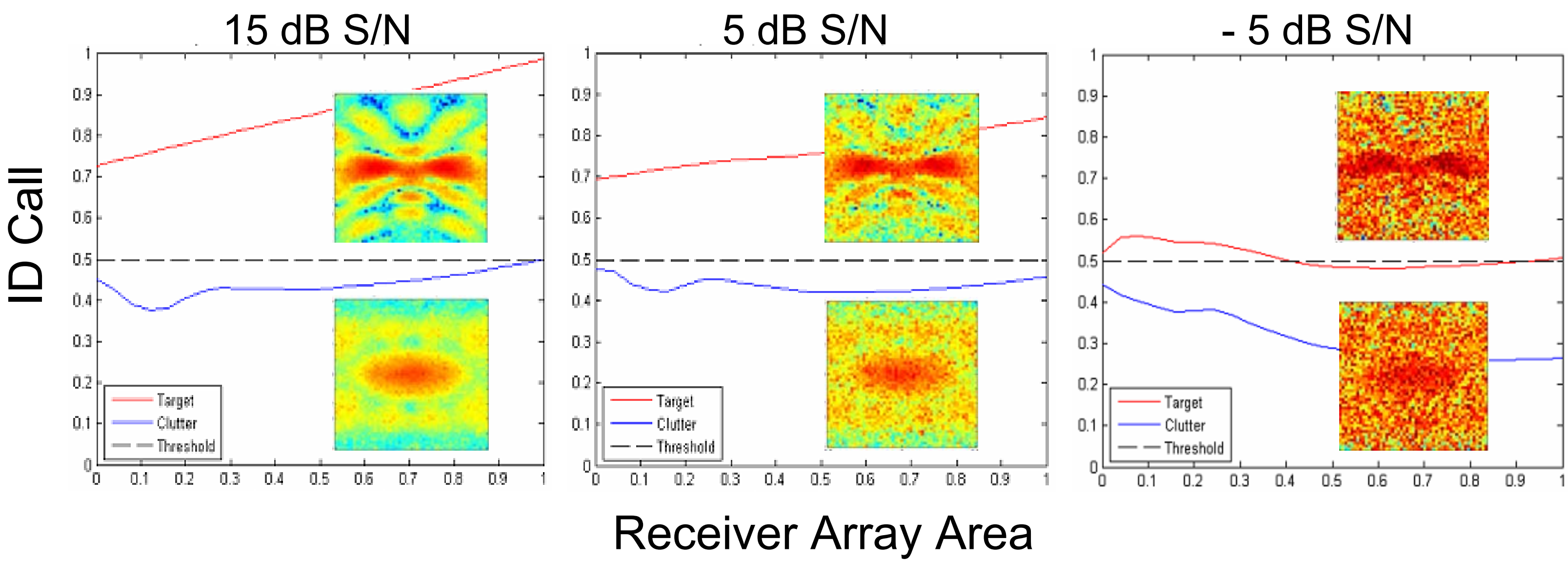
RVM Identification Algorithm Feature Spaces

Target Separation using Kernel for 2-D RVM

STARS3D Simulation



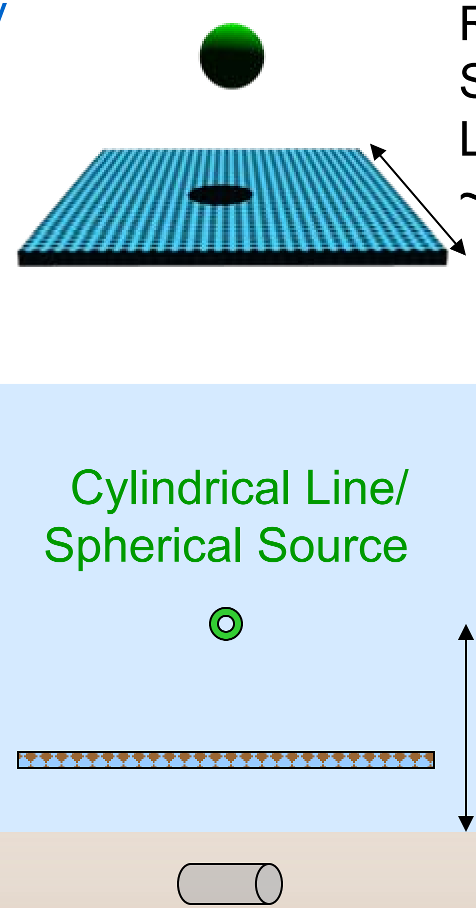
Simulations predict encouraging performance for initial 2-D RVM



New NAH Measurement Capability to Support Look-Down Search Scenario

Synthetic Array

Receiver Spacing (Virtual)
3 cm
λ / 2 @ 25kHz



Receiver Scan Length ~ 1m

Cylindrical Line/ Spherical Source

Source Height 1.25m

Receiver Height 20 cm

Buried UXO

NRL Sediment Pool Facility

New NAH Measurement Capability for Look-Down Search Scenario

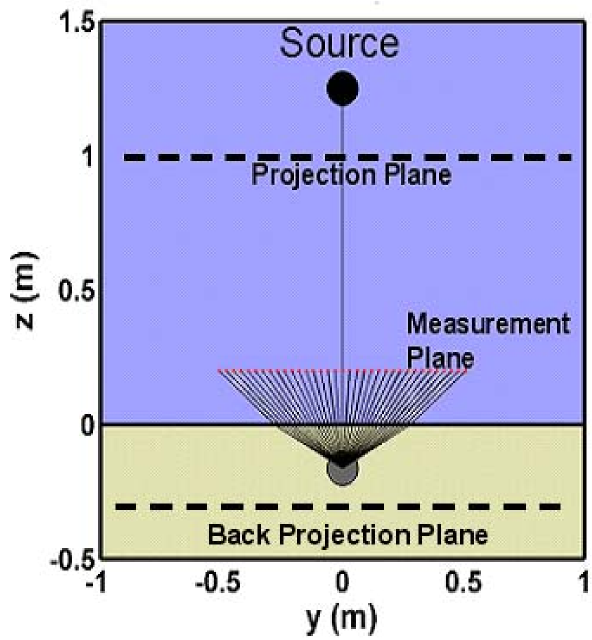
Data easily propagated up to higher positions

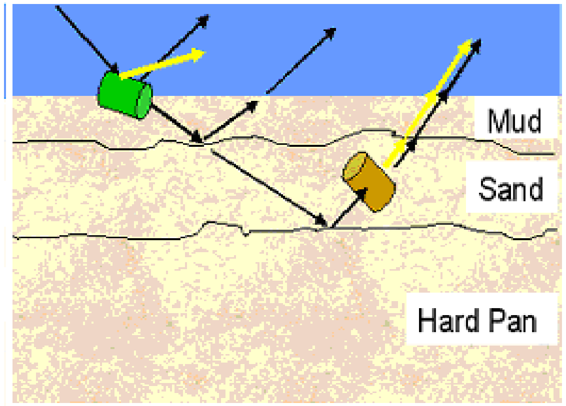
For lower part of the SA band, receiver distance << λ: nearfield hologram (*NAH)*

- *Do evanescent waves matter?*
- *Can we project to water/ sediment interface?*
- *Can we project to planes below interface?*

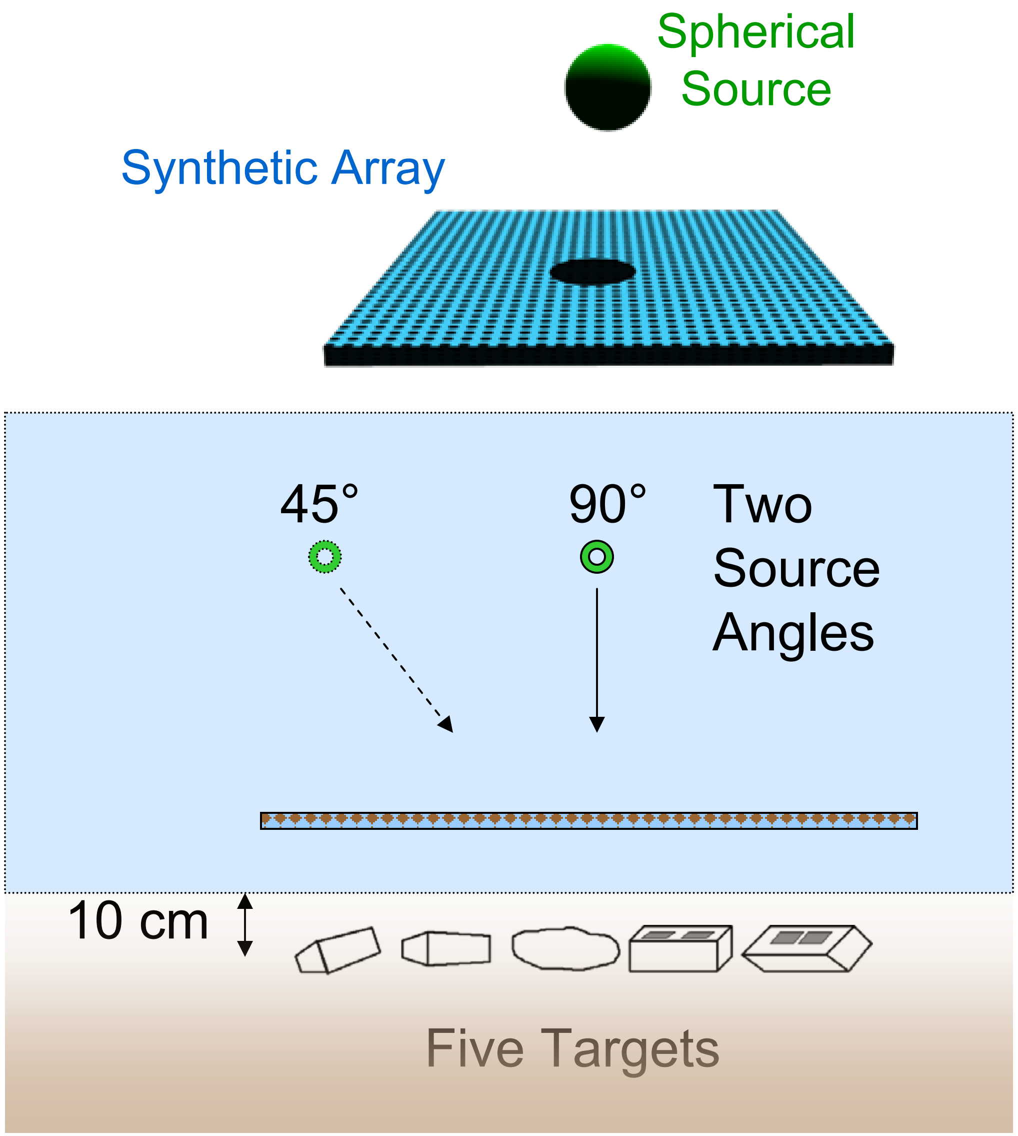
Construct velocity and intensity maps

- *Are the latter more effective for target ID?*



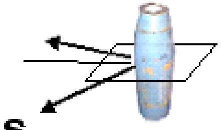


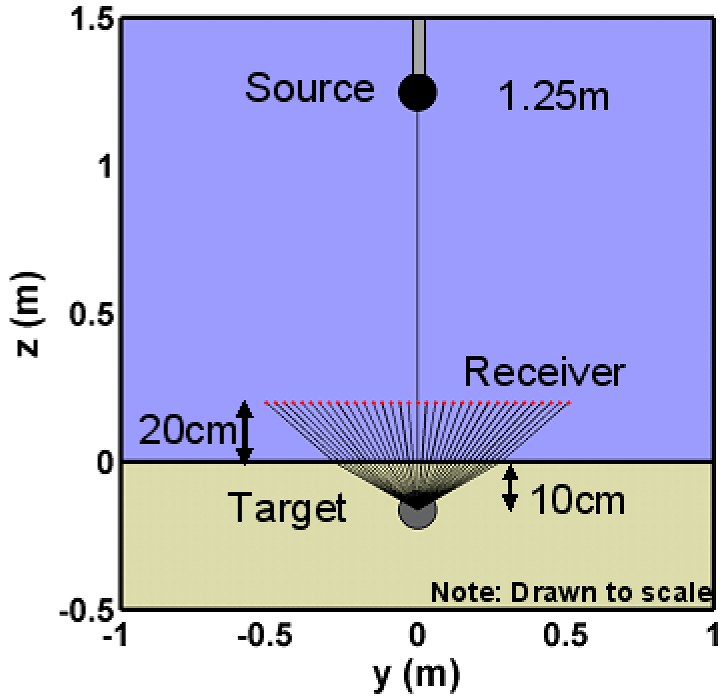
Buried Target Measurements in the NRL Sediment Facility

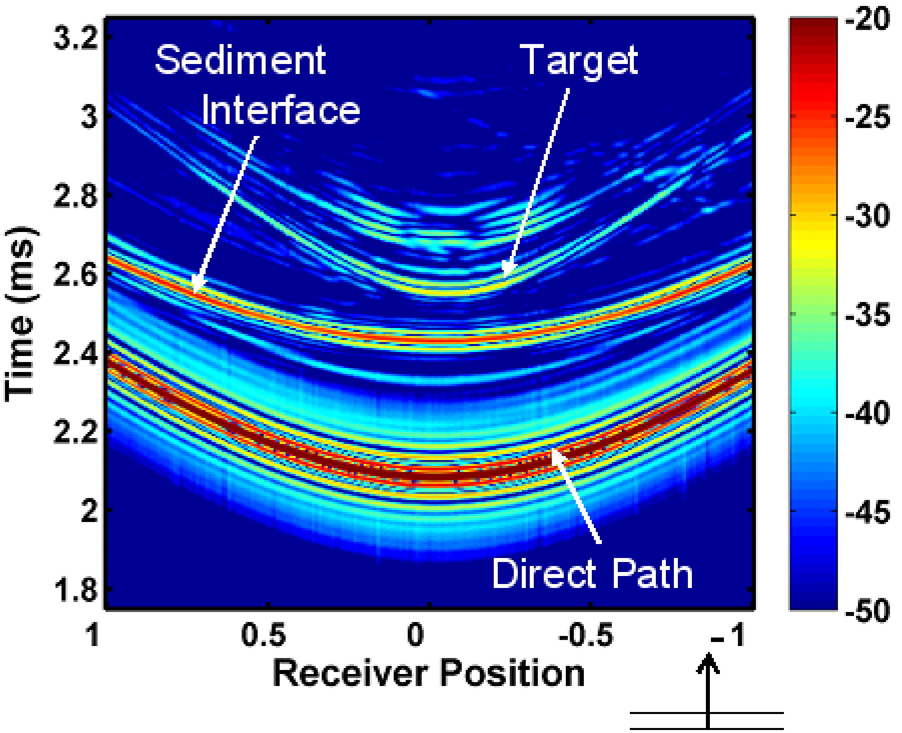


Preliminary measurements in NAH sediment facility

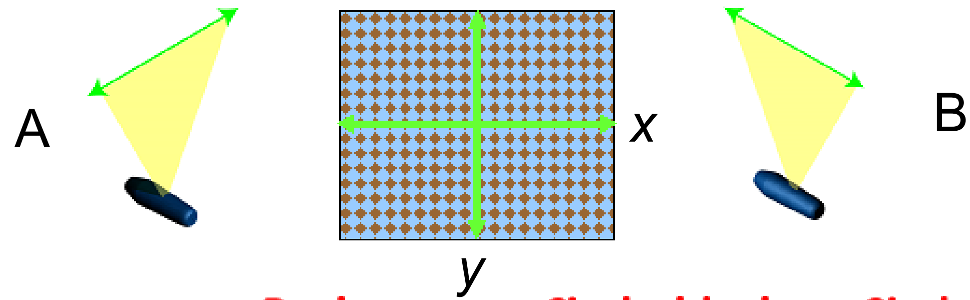
- **Geometry is known due to high precision robotic system**
- **Target returns are isolated by temporal windowing:**
  - **~ Use a ray-approximation to estimate time of flight values**

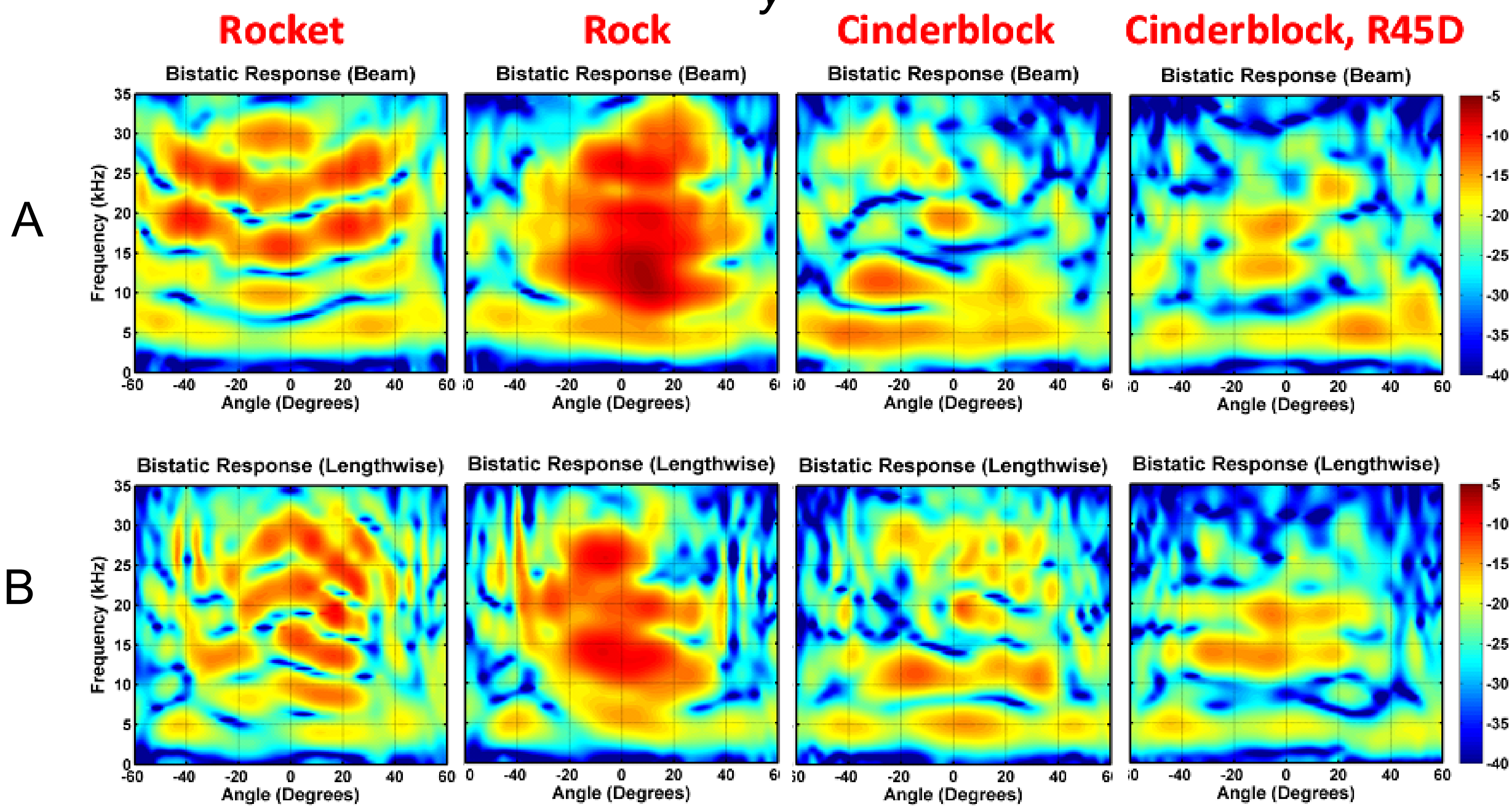




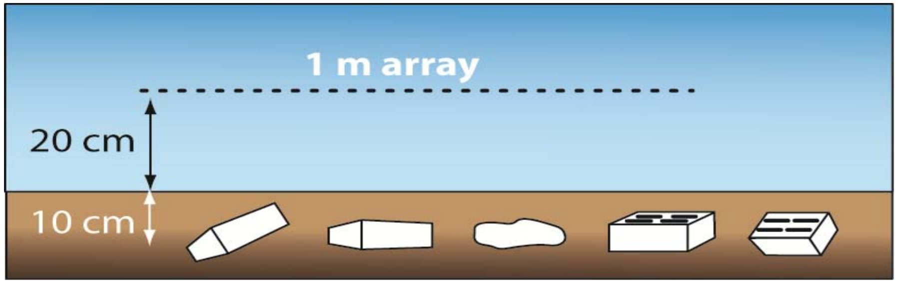


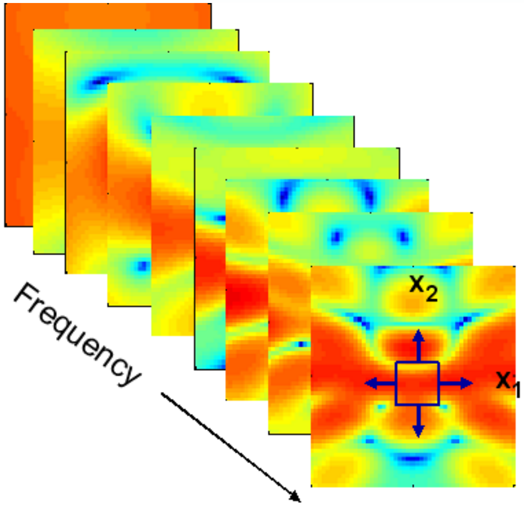
Target Strength vs Frequency / Angle Measured Along x and y Axis of Array



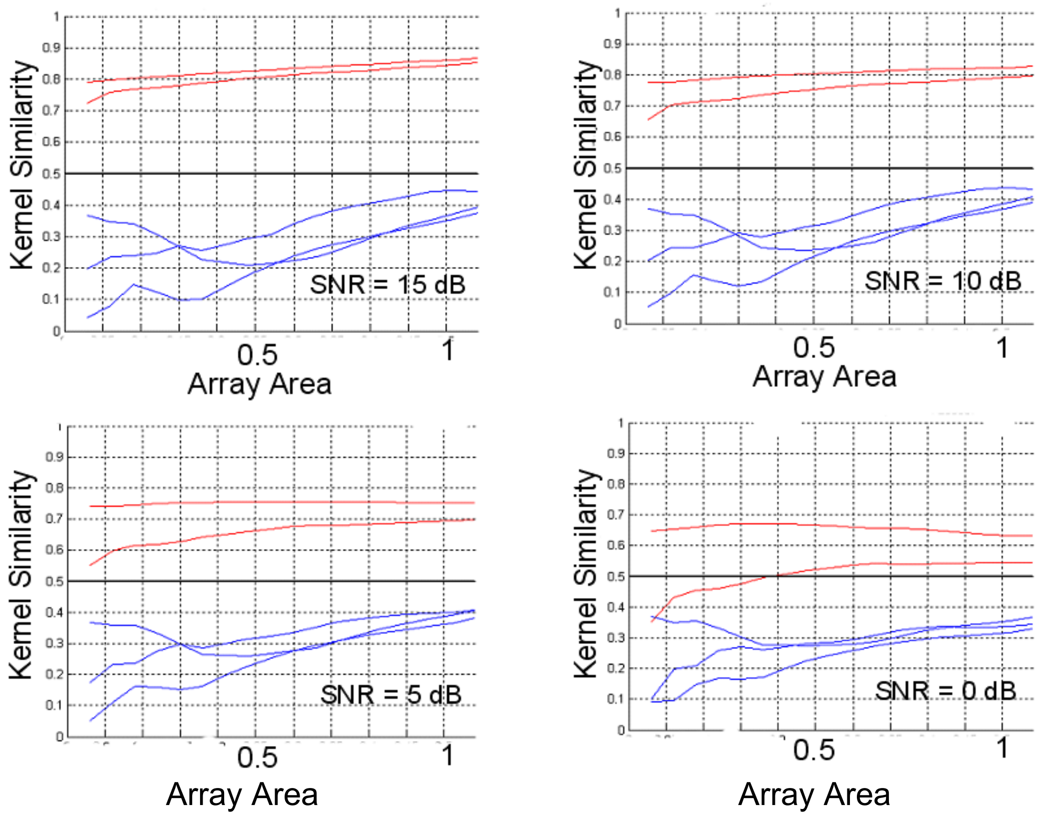


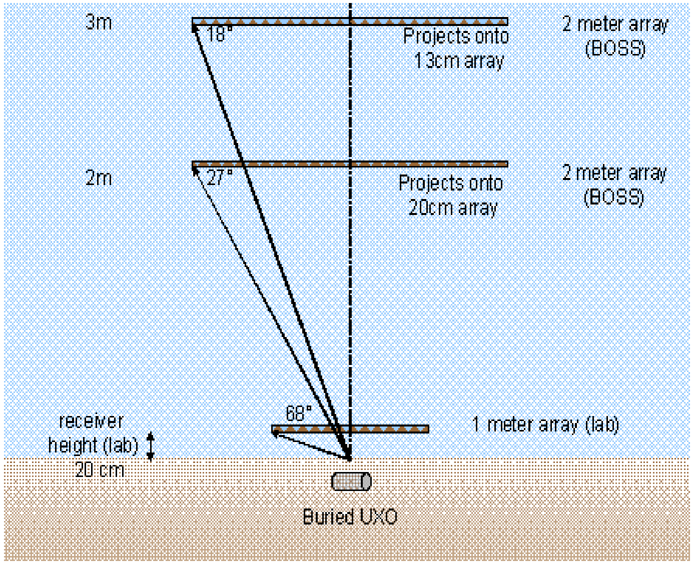
Feature-Based Target ID using Laboratory Data



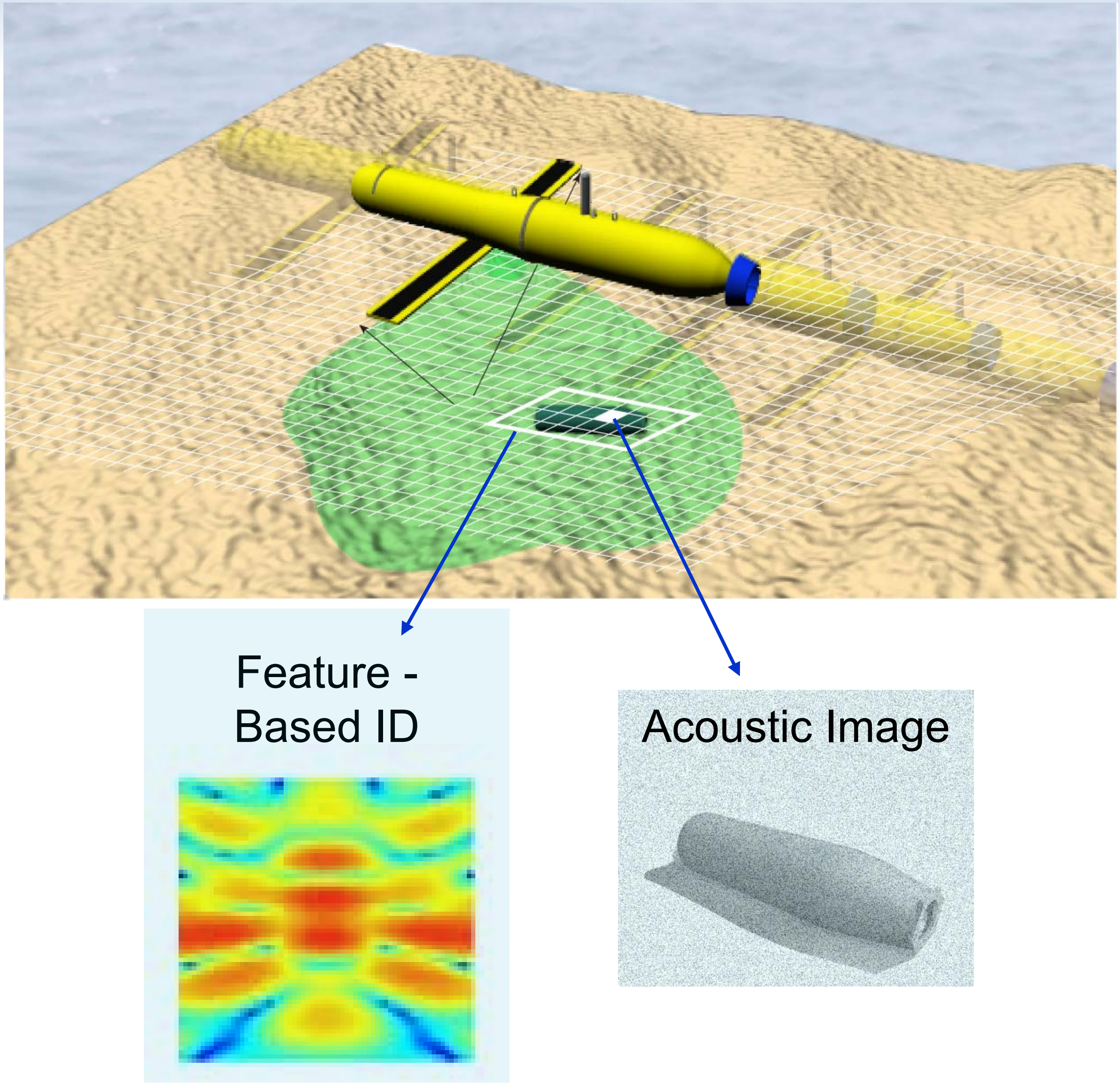


Rocket/False Target Feature Separation





Fusing SA Feature ID & Acoustic Imaging



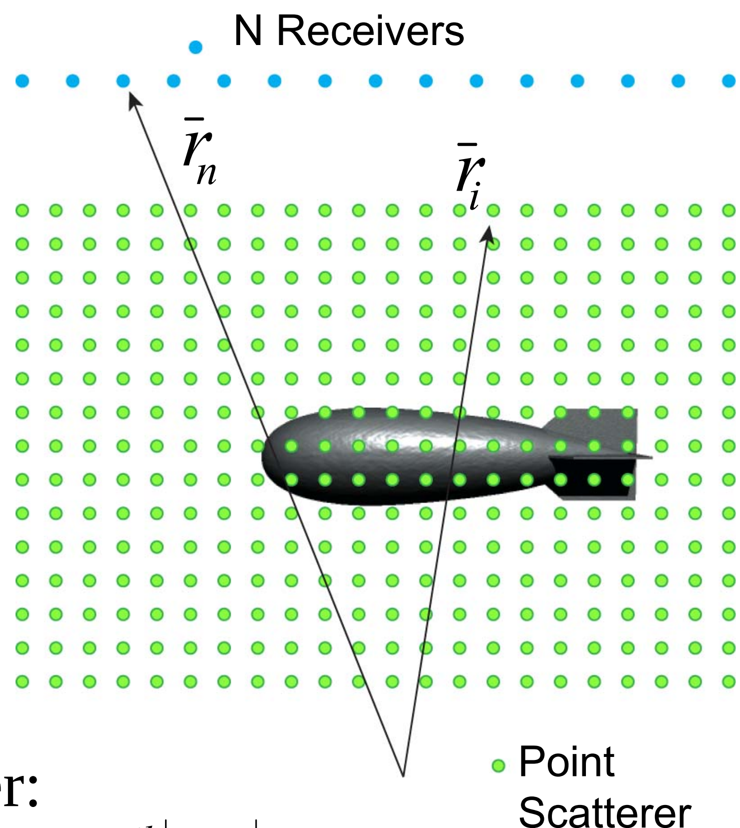
Imaging Algorithm

The pressure at receiver point r_n generated by a point scatterer located at r_i can be written as:

$$P_n(\bar{r}_n|\bar{r}_i,\omega) = -i\rho_0 kcQ_s(\omega)G(\bar{r}_n|\bar{r}_i,\omega)$$

where, $$G(\bar{r}_n|\bar{r}_i,\omega) = \frac{e^{ik|\bar{r}_n - \bar{r}_i|}}{4\pi|\bar{r}_n - \bar{r}_i|}$$

and Q_S is the volume velocity at $\bar{r}_i$ in response to the incident field.



We collect the source strength terms into a “scattering strength” parameter:

$$\underbrace{P_n(\bar{r}_n|\bar{r}_i,\omega)}_{\text{Pressure at } n^{th} \text{ Receiver}} = \underbrace{\sigma_i(\bar{r}_i,\omega)}_{\text{Scattering Strength}}\underbrace{V(\omega)}_{\text{Input Pressure Waveform}}\frac{e^{ik|\bar{r}_n - \bar{r}_i|}}{4\pi|\bar{r}_n - \bar{r}_i|}$$

Imaging Algorithm (Cont.)

The scattered pressure is then normalized by the incident signal,

$$D_n\left(\bar{r}_n\middle|\bar{r}_i,\omega\right)=\frac{P_n\left(\bar{r}_n\middle|\bar{r}_i,\omega\right)}{V(\omega)}=\sigma_i\left(\bar{r}_i,\omega\right)\frac{e^{ik\left|\bar{r}_n-\bar{r}_i\right|}}{4\pi\left|\bar{r}_n-\bar{r}_i\right|}$$

Solving for the scattering strength,

$$\sigma_i\left(\bar{r}_i,\omega\right)=4\pi\left|\bar{r}_n-\bar{r}_i\right|D_n\left(\bar{r}_n\middle|\bar{r}_i,\omega\right)e^{-ik\left|\bar{r}_n-\bar{r}_i\right|}$$

Taking the inverse Fourier transform, and assuming a perfectly reflecting point scatterer, *i.e.* $\sigma_i\left(\bar{r}_i,\omega\right)=\sigma_i=\text{Constant}$

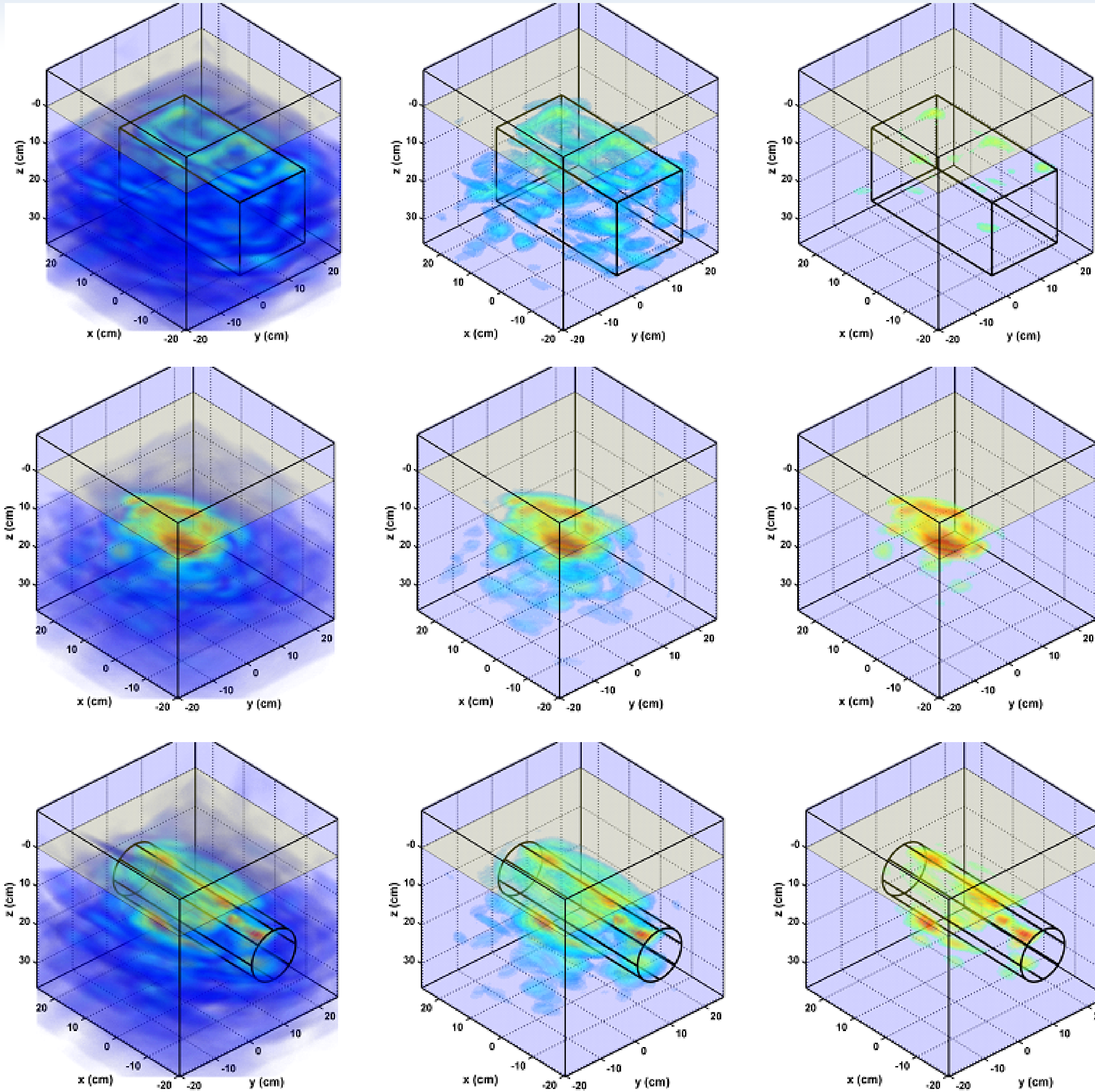
$$\sigma_i\left(\bar{r}_i\right)\delta(t)=4\pi\left|\bar{r}_n-\bar{r}_i\right|d_n\left(\bar{r}_n\middle|\bar{r}_i,t-\left|\bar{r}_n-\bar{r}_i\right|/c\right)$$

Multiply by $\delta(t)$, integrate over time, and average over all channels:

$$\text{Image Strength at } \bar{r}_i\equiv\sigma_i\left(\bar{r}_i\right)=\frac{1}{N}\sum_{n=1}^{N}4\pi\left|\bar{r}_n-\bar{r}_i\right|d_n\left(\bar{r}_n\middle|\bar{r}_i,\left|\bar{r}_n-\bar{r}_i\right|/c\right)$$

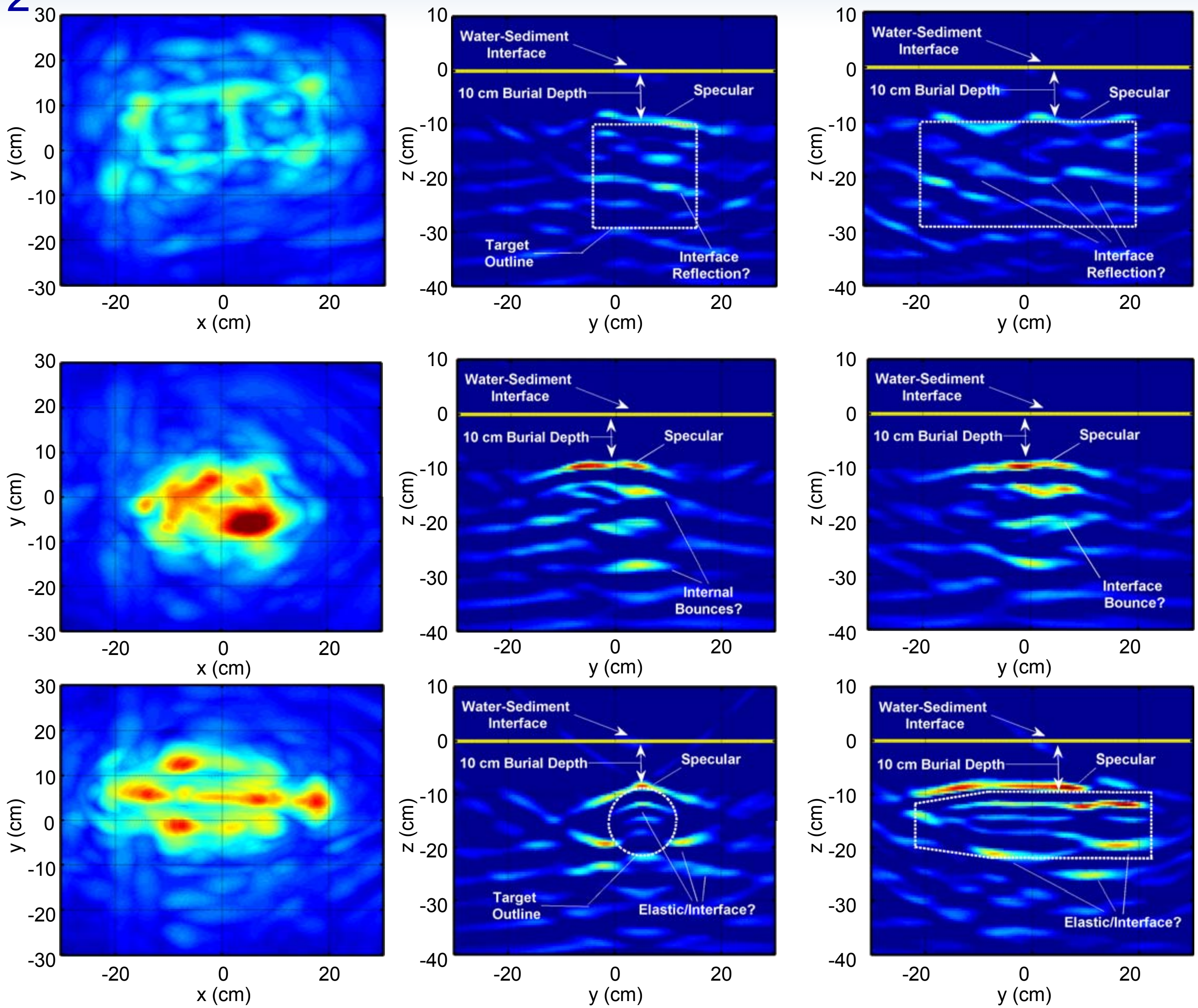
Volumetric Images of Buried Targets:

Imaging Band 12 – 25 kHz



2-D Images of Buried Targets:

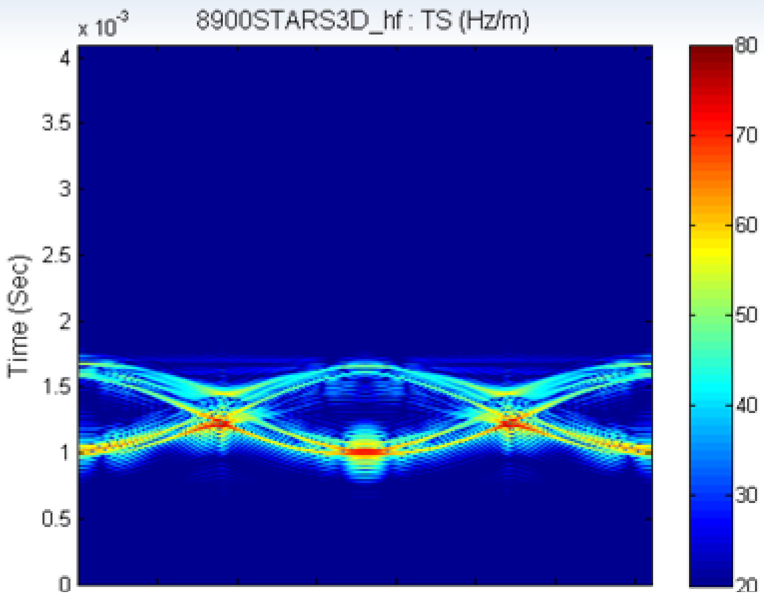
Imaging Band 12 – 25 kHz

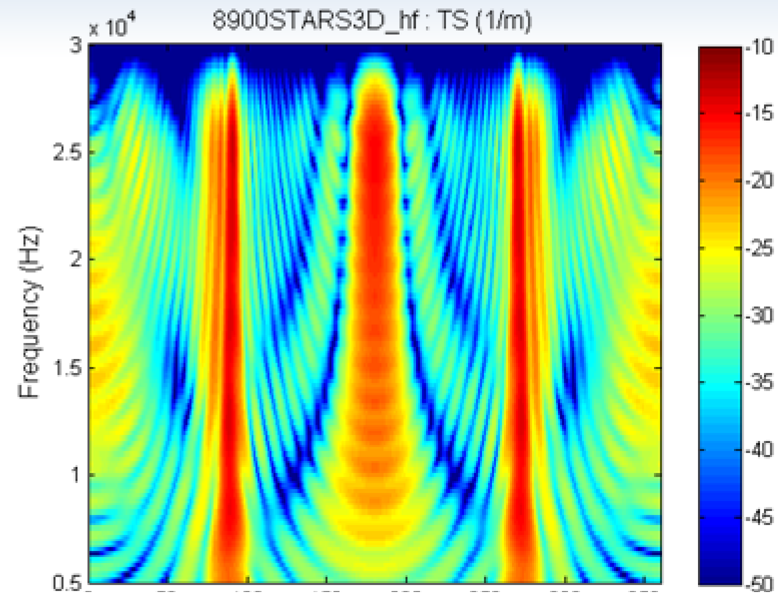


Time / Angle Plots for Rocket

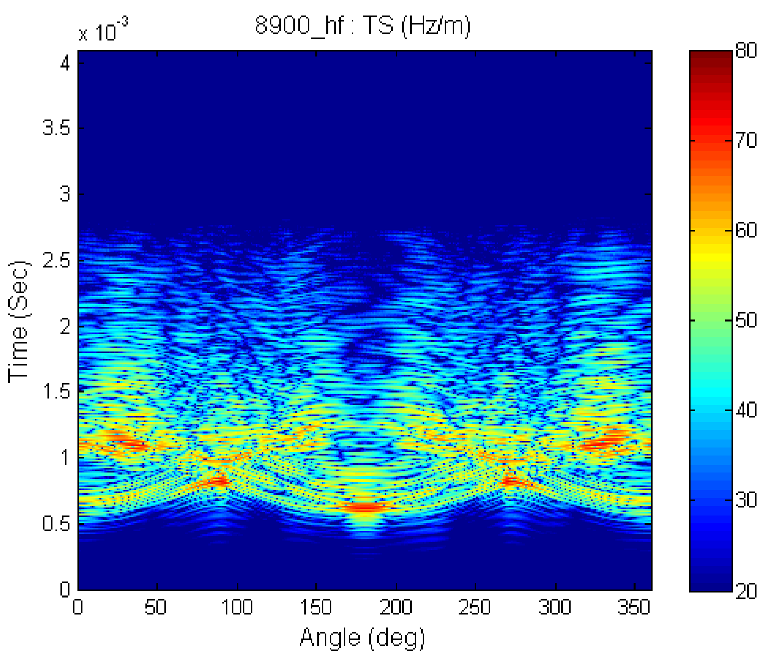
Time Domain

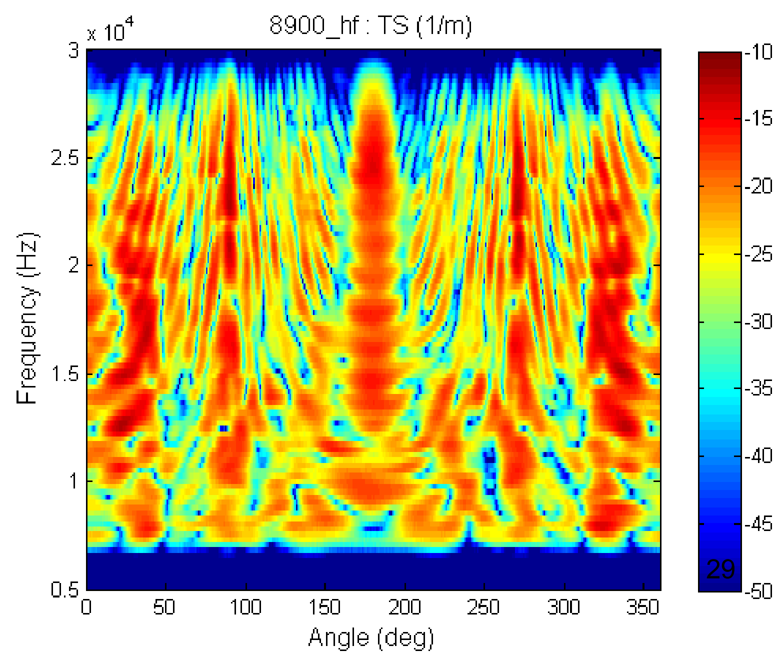
Frequency Domain





Only Specular

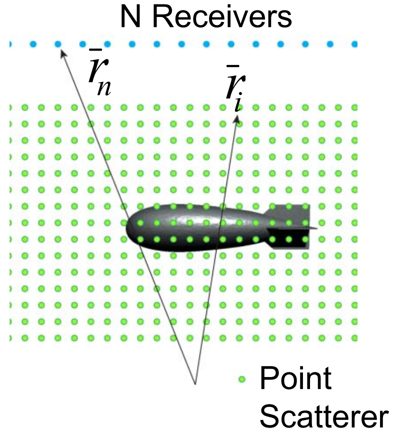




Full Response (Elastic)

Imaging and Specular Scattering

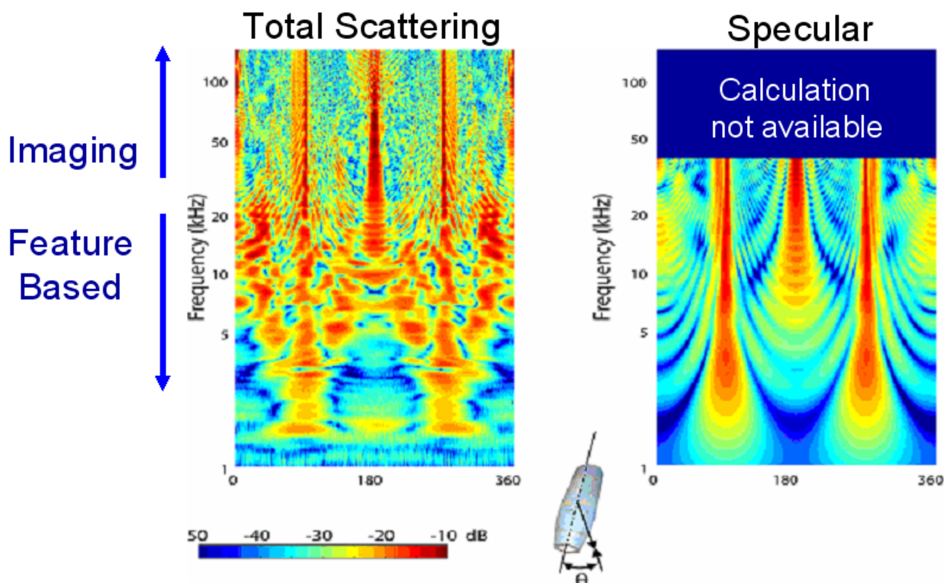
$$\text{Image Strength at } \bar{r}_i \equiv \sigma_i(\bar{r}_i) = \frac{1}{N}\sum_{n=1}^{N} 4\pi|\bar{r}_n - \bar{r}_i| d_n\left(\bar{r}_n \middle| \bar{r}_i, |\bar{r}_n - \bar{r}_i|/c\right)$$



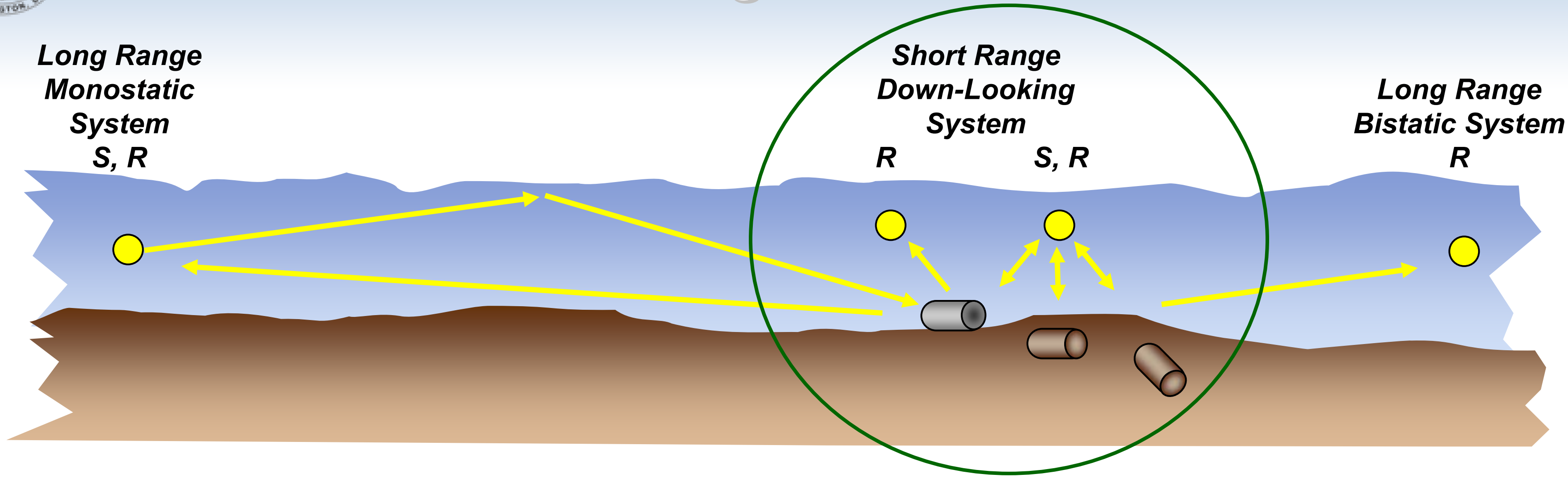
For specular scattering

$\sigma_i(r_i)$ non-zero only on target surface

Where is specular scattering expected to be dominant?



Concluding Remarks

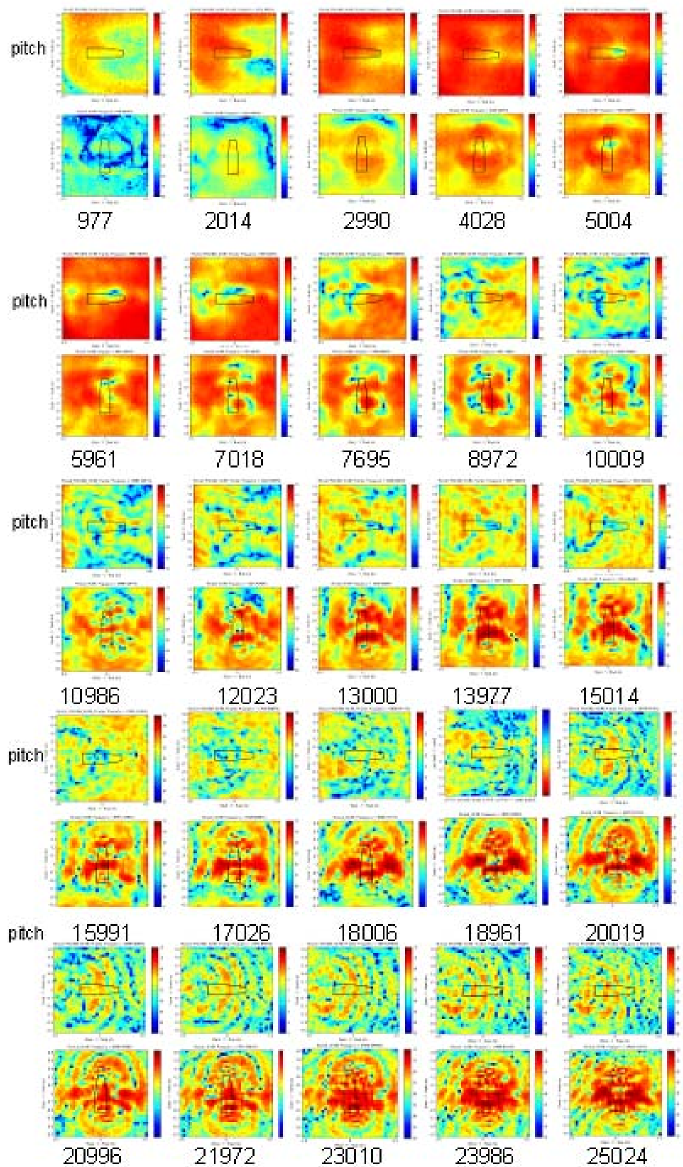


In our new focus on the short range down-looking scenario our plans are to :

- Develop a RVM structural acoustic ID algorithm methodology which includes burial effects and target “pitch” angles in the training
- Fuse structural acoustic and image ID algorithms, perhaps in an interactive manner
- Move to marine environments and naturally occurring clutter

Backup Slides

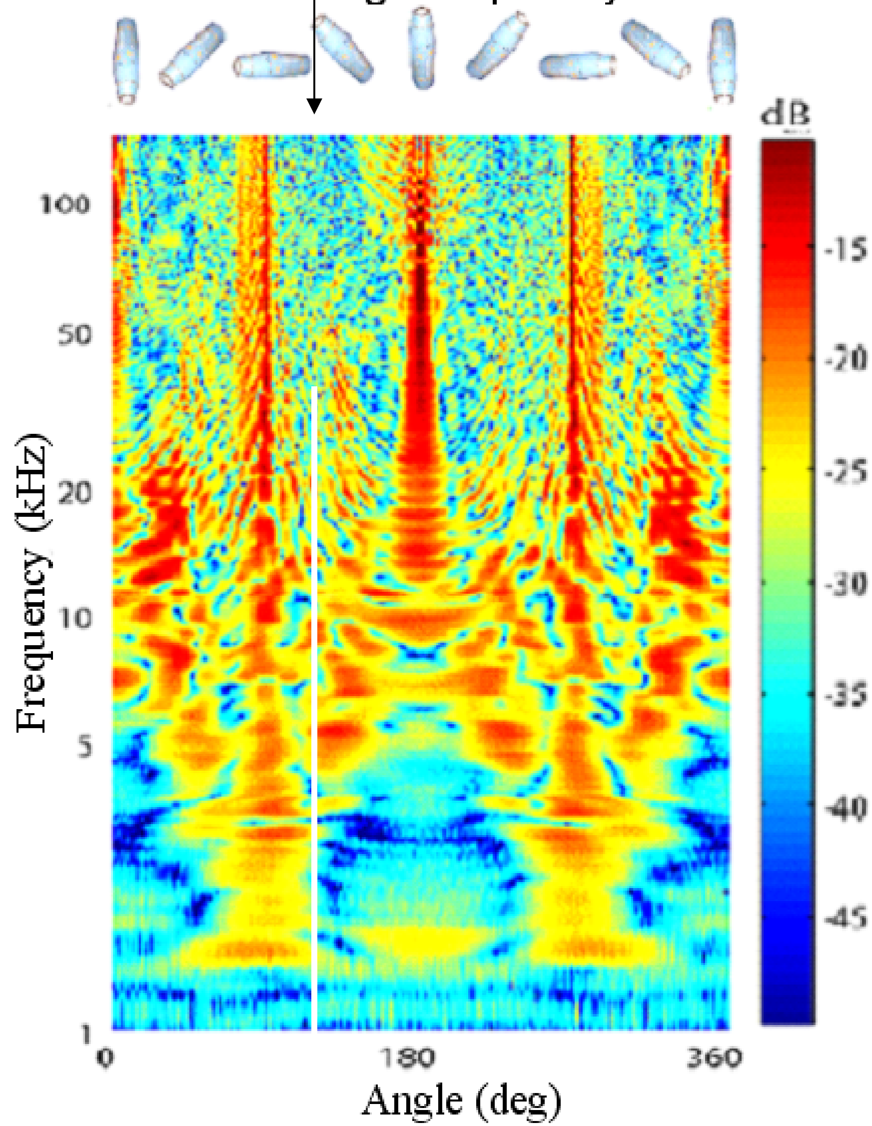
Scattered pressure over receiver array for 5 inch rocket buried at 30° downward pitch angle for frequencies in Hz

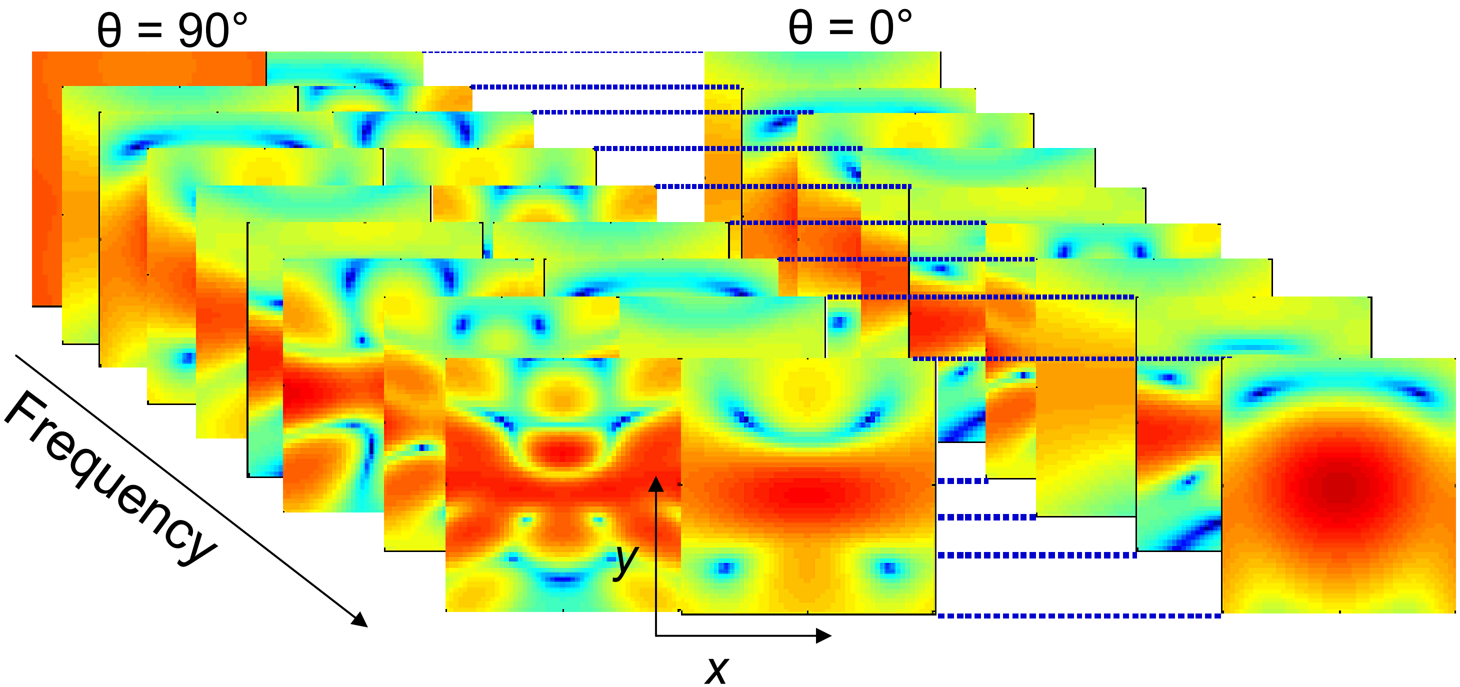


Free-field mono-static TS

30° downward nose pitch

Semi-Log Frequency Plot





θ = 90°
θ = 0°
Frequency
y
x